

**Modification of Flow Model and Pumping Strategies for Cleanup
and Capture of TCE and DCE Plumes Near Mission Drive,
Wurtsmith Air Force Base, Michigan**

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1. INTRODUCTION

Utah State University (USU) and Parsons Engineering Science (PES) were tasked by the Air Force Center for Environmental Excellence to:

- (1) Modify the three-dimensional basewide ground-water flow model for Wurtsmith Air Force Base (WAFB), Michigan (PES, 1997) based on recent investigation by ICF Kaiser (ICF).
- (2) Develop contaminant transport models for OT-24 area TCE and DCE plumes. These models will use the same parameters that were used by ICF in their feasibility study..
- (3) Use the flow and transport models to develop optimal pumping strategies to achieve cleanup and capture of the plumes.

2. BACKGROUND

In a recent project, USU and PES developed a simulation/optimization model for the Mission Drive Pump-and-Treat system (PES, 1997). Recent field investigation by ICF showed that two improvements need to be implemented within the developed simulation model to better reflect field conditions. First, when USU used the PES flow model, simulated pathlines showed that contaminants would travel west of the Three-Pipes Drainage Ditch (3PDD) towards the Au Sable River. However, ICF's field investigation indicated that TCE is not migrating into the swampy area west of the Ditch.

The second improvement was related to aquifer base elevations. The elevations used in the PES model were, on average, 4 feet lower than elevations measured by ICF in their recent field investigation of the OT-24 area (ICF, 1996). The difference between PES model base elevations and ICF-measured elevations ranged between 1 and 11 feet.

USU also suggested improving the accuracy of three-dimensional flow near river cells. In the PES model, most river cells penetrated the entire thickness of the aquifer. USU revised the model (as described below) to better reflect 3-D flow patterns near surface water features.

The last modification for the flow model was related to the slow simulation convergence of the PES flow model. The saturated thickness in the top model layer was very small at the Arrow Street wells. This resulted in slow convergence of computed heads for some scenarios. Slow

convergence can lead to excessive time requirements in using the flow model. It can also mean that groundwater heads and flows computed near the Arrow Street wells are less accurate than elsewhere. USU suggested modifying the flow model (as described below) to achieve faster convergence.

Figures 1 and 2 show the finite difference grid and the boundary conditions used in the flow model. Facility background, aquifer description, and plume history can be found in several reports including those by PES (1997) and ICF (1996). Information about the conceptual model, model setup, boundary conditions, grid design, and other assumptions are presented by PES (1997).

3. MODEL MODIFICATION

As described above, modification of the PES flow model was necessary to (1) better represent the aquifer base at the OT-24 area, (2) better represent flow conditions near the 3PDD, and (3) better represent flow near surface water bodies. In the following sections, we describe the changes made to the flow model in order to achieve the stated goals.

3.1. Aquifer Bottom Elevation

USU used two sources of data to represent aquifer base elevations. The first source is the two-dimensional flow model developed by ICF (1996) for the OT-24 area. The second source is the PES model (PES, 1997). The ICF model covered an area in the center of the eastern part of the PES model. To incorporate the ICF elevations into the PES model, we developed an algorithm that proceeded as follows for each cell in the PES model.

1. If the cell is outside the area covered by the ICF model, do not change its bottom elevation.
2. If the cell is inside the area covered by the ICF model, find the cell in the ICF model whose center is closest to the center of the PES model cell. Use the bottom elevation from the ICF model as aquifer bottom elevation (elevation of bottom of layer 3). Then check the aquifer thickness of model layer 3 and change the top elevation of model layer 3 so that at least 3 feet of aquifer thickness is used in all cells representing model layer 3. Finally, increase hydraulic

conductivity by 30% for the model layer 3 cells whose thickness has been decreased. The 30% is the optimal change which resulted in the best match between target head values and simulated heads from the model.

3. After all cells are assigned bottom elevation values, smooth the transition between the unchanged and changed values. Smoothing was performed so that the change in bottom elevation between each pair of adjacent cells in the model is no more than 4 feet.

This approach reduces the saturated thickness for model layer 3 without changing saturated thickness for most cells in model layers 1 and 2. Figures 3, 4, and 5 show the bottom elevations for model layers 1-3, respectively. Hydraulic conductivity values for all model layers are shown in Figures 6, 7, and 8.

3.2. Three-Pipes Drainage Ditch Area

Recent investigation by ICF indicated that the area west of the 3PDD is a swampy area and the aquifer material is mostly clay. ICF modeled that portion of the aquifer using a low hydraulic conductivity (10 ft/day). This was not accounted for in the PES model (PES, 1997). USU approximated the ICF representation for this area, but used three layers instead of the ICF model's single layer. Therefore, USU assigned the low hydraulic conductivity value to all model layers. This representation of the 3PDD improves flow simulation because simulated contaminated groundwater pathlines from all model layers enter the 3PDD and do not migrate towards the Au Sable River. This supports the findings by ICF (1996) that showed that TCE does not migrate west of the 3PDD towards the Au Sable River. Figures 9, 10, and 11 show pathlines of particles after being placed along an east-west line just north of 412,000 Northing in model layers 1, 2, and 3, respectively. All particles in the area immediately east of Mission Drive travel to the south and enter the 3PDD. Other particles further east travel to the southeast and south towards the Au Sable River. The dark lines in these figures show pathlines that are very close to each other. Note that these figures are generated using the modified model with calibration conditions. Under these conditions, the Mission Drive wells are pumping.

3.3. Model River Cells

In the PES model, most river cells used to represent the Au Sable River and other surface water features were assumed to fully penetrate all model layers. This resulted in somewhat inaccurate vertical flow patterns near the river cells. USU changed all river cells so that they only penetrate model layer 1. In model layers 2 and 3, USU replaced river cells at the edge of the study area with constant-head cells. For internal cells, river reaches were removed from layers 2 and 3. Then river conductance was increased for some river reaches to achieve roughly the same total river-aquifer interflow as the PES model interflow. River conductance values were changed until model-simulated heads matched target heads very well. Calibration statistics are listed in Section 3.5.

3.4. Arrow Street Area

The PES model had computational difficulty in providing stable head values near the Arrow Street extraction wells. The reason for this instability was that the saturated thickness of model layer 1 was small in some locations. The MODFLOW re-wetting option often creates numerical instabilities when an extraction well pumps from an aquifer having a small saturated thickness. To avoid such instability, USU dropped the bottom elevations of model layer 1 by up to six feet in the Arrow Street area. This reduces layer 2 thickness but does not affect total aquifer thickness because aquifer bottom elevations were not changed. The change is justifiable because the elevations separating layers 1 and 2 are relatively arbitrary and are not based on clear stratigraphic differences.

3.5. Modified Calibration

Calibration of the flow model demonstrates that (1) the model represents all major features of the aquifer and (2) the model can provide acceptable predictions for steady-state water levels. Groundwater levels from 72 observation wells were used as calibration targets. These are the same observation wells used by PES in the original calibration. Measured water levels were available from three time periods: August 1993, August 1994, and May 1995. For the steady-state calibration, USU followed the PES procedure. Water levels at each well were averaged for the

three time periods. This coincides with the time frame of the pumping data that were used to compute average pumping rates for the wells in the model.

A steady state calibration is performed because a transient calibration requires more precise knowledge of how pumping changed with time. Furthermore, water levels at some monitoring wells are not available for all three time periods. Finally, the plume capture strategy will also assume steady state conditions.

In general, calibration accuracy is evaluated using residuals -- the smaller the residuals, the better the calibration. Residual values were computed at each observation location by subtracting the simulated groundwater head from the average observed head. Because the modified flow model provides a slightly better match to observed (target) heads than the original PES model, the residuals are generally smaller for the modified model. Table 1 contrasts residuals from the PES and modified models. Figure 12 compares simulated and target heads and shows a histogram of the residuals. Figures 13, 14, and 15 show simulated groundwater heads and residual values (at observation wells) for all model layers. A diskette attached to this report contains the input files for all models used.

TABLE 1. Calibration statistics for PES and modified models

Criterion	PES Model	Modified Model
Mean Residual (ft)	0.976	0.519
Mean Absolute Residual (ft)	1.217	1.016
Root Mean Squared Residual (ft)	1.573	1.333

Note: Root mean squared (*RMS*) is defined as

$$RMS = \sqrt{\left[1/N \sum_{i=1}^N (h_{t,i} - h_{s,i})^2 \right]}$$

Where $h_{t,i}$ and $h_{s,i}$ are the target head and simulated head, respectively, at the i^{th} location and N is the number of target head values.

4. OPTIMIZATION PROBLEM DESCRIPTION

This section presents an optimal pumping strategy designed to cleanup and capture the TCE and DCE plumes near Mission Drive, Wurtsmith Air Force Base. Capturing the contaminant plumes (as defined below) prevents further spreading of the contaminants into clean areas of the aquifer. Another goal of the presented strategy is to achieve cleanup of the contaminated aquifer within a six-year period. We also present several modifications of the optimal pumping strategy that can achieve aquifer cleanup within shorter time periods. Figures 16, 17, and 18 show the TCE plume existing at different depths in August 1996. Figure 19 shows the DCE plume in the second model layer. No DCE concentrations exceeding 230 ppb have been detected in the first and third model layers. The 94 ppb TCE concentration goal is the Michigan regulatory limit for the groundwater/surface water interface. Michigan has not specified a groundwater/surface water interface criteria for DCE. Therefore, WAFB specified we use the 230 ppb chronic fresh water ambient water quality criteria for DCE.

It is assumed that a newly adopted pumping strategy will be used in lieu of the pumping of the existing Mission Drive pump-and-treat (P&T) system. The background pumping used to develop the new strategy includes all pumping rates considered in the calibration except that from the Mission Drive P&T system.

As requested by AFCEE and WAFB, we developed the pumping strategy using the following:

- (1) the three-layer MODFLOW groundwater flow simulation model and data described previously.
This three-layer model permits representing 3D flow in what is essentially a single-layer aquifer in the field.
- (2) two three-layer MT3D groundwater transport models. One is applied to each contaminant (TCE and DCE) plume. The MT3D models address the contaminated portion of the area modeled by MODFLOW.
- (3) plume data discretized by Waste Policy Institute (WPI) from data provided by ICF into cells comprising the flow model.
- (4) the REMAX simulation/optimization (S/O) model. REMAX:

- predicts system response to pumping either directly (like a normal simulation model) or via discretized convolution expression. The convolution approach utilizes linear systems theory and influence coefficients obtained by normal simulation. REMAX employs MODFLOW or other simulation model for either normal simulation or to develop influence coefficients for simulation by convolution.
 - utilizes a convolution approach that is adapted to accurately address nonlinear as well as linear systems.
 - formulates and organizes all equations needed to solve a user-specified optimization problem.
 - solves the optimization problem using robust large-scale optimization solvers.
 - can compute optimal pumping strategies for a wide variety of groundwater management problems--including plume capture, contaminant removal, regional planning, conjunctive water management, and other applications.
- (5) the MODPATH model to delineate proposed well capture zones. USU assembled the MODPATH data set using the modified flow model, and the porosities ICF used in a feasibility study.

The presented strategies do not employ any existing extraction wells. The results are shown in a later section. Considering current plume definition, the existing Mission Drive wells are not optimally designed for plume capture/cleanup. Thus no existing wells are included in the proposed feasibility pumping strategies. Preliminary optimizations considered 24 possible extraction well locations simultaneously. The 24 potential extraction wells were placed inside the TCE and DCE plumes. The optimization procedure (described in Section 4.2) selected (from these 24 possible wells) the set of wells and rates that achieve the maximum possible plume cleanup.

4.1. Treatment Facility Capacity

The Mission Drive treatment facility (air stripper) at WAFB is currently processing about 200 gpm. According to the air stripper manufacturer (Tri-Mer Corporation), the stripper can handle larger rates of contaminated water but the removal efficiency will decrease (Table 2).

TABLE 2. TCE removal efficiency versus inflow rate for the existing air stripper (source: Tri-Mer Corporation).

Liquid Inflow Rate (gpm)	Removal Efficiency (%)
300	99.2
400	98.5
500	97.2
600	95.0

$$\text{Removal Efficiency} = \frac{100 \% (\text{inflow concentration} - \text{outflow concentration})}{\text{inflow concentration}}$$

Increasing inflow will cause nonlinearly greater efficiency declines. Removal efficiency will drop more rapidly as the packing begins to flood. The upper limit on acceptable inflow rate depends on the contaminant concentration of the inflow and the desired outflow concentration. For example, if the average inflow concentration of TCE is 900 ppb and the outflow concentration should not exceed 94 ppb, the removal efficiency should be at least 89.5 percent. Therefore the inflow rate can exceed 600 gpm. For the same inflow concentration, if outflow TCE concentration should not exceed 5 ppb, the removal efficiency must be at least 99.4 percent, and flow should be something less than 300 gpm (possibly close to the current 200 gpm).

Assuming the TCE plume concentrations provided by ICF and reasonable mixing of extracted groundwater, the average TCE concentration entering the treatment plant will probably not exceed 400 ppb. If the desired treatment plant outflow TCE concentration is 5 ppb, plant inflow can be close to 400 gpm.¹

¹ Because the DCE Henry's Law Constant is about two thirds that of TCE, DCE is a more difficult to volatilize than TCE. However, concentrations of DCE are less than those of TCE at the site, and the DCE cleanup goal is higher than that of TCE. Assuming insignificant interference between the two contaminants, acceptable DCE removal will probably also be achieved.

The current discharge permit for the treatment facility does not allow the TCE concentration for treated water to exceed 1.5 ppb. However, this permit is being modified to allow this concentration to be as much as 5 ppb. Below, we develop pumping strategies for both situations.

4.2. Optimization Problem Formulation

The developed pumping strategy is to address a target area defined as: south of Perimeter Road, North of southern edge of the current P&T system capture zone, East of Mission Drive, and West of the 94-ppb TCE or 230-ppb DCE contours, whichever extends further east. Contaminants lying south of the current capture zone are assumed to migrate towards the 3-Pipes Drain. Recent field investigation by ICF has indicated that the drain will capture such contaminants. The modeling results in Section 3.2 also support that assumption. TCE concentrations needing capture (above 94 ppb) exist in PES model layers 1, 2, and 3 (Figures 16, 17, and 19). DCE (above 230 ppb) needs capture only in model layer 2 (Figure 18). The lateral extent of the TCE and DCE plumes and the location of the hot spots differ with contaminant.²

Any proposed pumping strategy must satisfy the following conditions.

1. It must capture TCE and DCE plumes within the target area. It must cause TCE and DCE concentrations within the target area to drop below 94 and 230 ppb, respectively, within 6 years.
2. It must have a total flow rate not exceeding 400 gpm with an average concentration less than 400 ppb, if possible.
3. It must be developed assuming steady-state groundwater flow.
4. The lower bound on pumping for each potential well is zero. The upper bound on pumping rate is the maximum sustainable rate (between 90 and 160 gpm). The maximum sustainable rate was determined using the flow model assuming the same boundary conditions and pumping rates used in the calibration, excluding Mission Drive pump-and-treat wells. A sustainable rate is one which does not cause complete dewatering of the respective aquifer layer in the flow model.

5. For proposed wells screened in multiple layers, the proportion of total extraction assigned to each layer is proportional to the layer's modeled transmissivity (In the model, screen length must equal layer saturated thickness. This can be changed in field design).
6. No treated water is injected to the aquifer.
7. Capture zones of each proposed extraction well are delineated using backward particle tracking from the well.
8. Since the three model layers present a single aquifer, no effort is made to control vertical contaminant movement. For all performed simulations including developed strategies, there is no consistent vertical gradient trend in the plume area. However, forward tracking will be performed for particles placed around the plume edges to ensure three-dimensional capture of all plumes.

USU assumed a primary goal of determining the set of pumping rates and well locations that will maximize contaminant mass removal while satisfying the above conditions 1-6. Before selecting this approach, USU evaluated five objective and constraint formulations described in Appendix A. Subsequently, pumping strategy design involved two steps. In the first step, USU determined the pumping rates to maximize contaminant mass removal subject to conditions 2 through 9. USU used these pumping rates as background pumping for the second step. In the second step, USU determined the minimum extra pumping (beyond that determined in step 1) needed for plume capture subject to conditions 1 through 9.

The optimization problem formulated in step 1 is solved using an artificial neural network combined with a genetic algorithm (Aly and Peralta, 1997). The optimization problem formulated in step 2 is solved using a response matrix approach (Peralta and Aly, 1997).³

² These TCE and DCE plumes are assigned to the modified model layers by WPI. WPI used the TCE and DCE concentrations provided by ICF and assigned them to the model cells and layers using block kriging. WPI has used professional judgement for assigning few concentration values to the model layers.

³ We used 12 potential extraction wells. REMAX selected 3 of these wells and determined the pumping rates for the selected wells.

5. PROPOSED PUMPING STRATEGIES⁴

Using the optimization formulation described above, we first developed a pumping strategy (Strategy A) that requires 265 gpm of extraction and achieves plume cleanup and capture. This Strategy is shown in Table 3. Figures 20-23 show the pathlines resulting from implementing pumping Strategy A.

Strategy A achieves cleanup and capture of both plumes using wells P1-P7. Wells P1, P2, and P3 extract from all model layers. Well P4 extracts from model layers 1 and 2. Wells P5, P6, and P7 extract only from model layer 2. Wells P6 and P7 are placed as far east in the DCE plume as necessary to capture the eastern part of the DCE plume in model layer 2.

We then developed other pumping strategies that enhance the cleanup resulting from Strategy A. Table 4 shows six alternative pumping strategies. All pumping strategies use the same well locations. Furthermore, the pumping rates for wells P5, P6, and P7 are the same for all strategies. The strategies differ in the pumping rates for wells P1 through P4. For each of these strategies, we used MT3D with MODFLOW to predict the concentrations resulting from implementing each pumping strategy. For each strategy, the pumping rates are used as input to MODFLOW to simulate steady state flow conditions. The resulting flow field is used twice as input to MT3D -- once to predict TCE concentrations and again to predict DCE fate. TCE and DCE concentrations dropped below 94 and 230 ppb, respectively, after 6 years. In the MT3D simulations, we used the same assumptions used by ICF (1996). That is, no degradation is considered and a retardation factor of 1.97 is used for both contaminants.

We also used MODPATH with MODFLOW to predict pumping strategy capture zones. For example, we used Strategy A pumping rates as input to MODFLOW. MODFLOW computed the steady state potentiometric surfaces that would result. Then we created a MODPATH data set with particles immediately around each recommended well. Twenty-five particles were placed around each well in the middle of the saturated thickness of each model layer. We used MODPATH to compute the paths these particles would follow to reach the wells (backtracks).

⁴ The strategies presented in this report differ from those presented in the October 1996 letter report by USU. The major difference is that the new strategies extract water mainly from model layers 1 and 2. In October 1996, lack of knowledge about aquifer base elevations affected well placement. Another difference is that the presented strategies assure both plume cleanup and capture. The strategies presented in October 1996 were designed mainly to achieve capture, although an effort was made to enhance cleanup.

If Strategy A is implemented, the transport model predicts that the TCE and DCE concentrations drop below 94 and 230 ppb, respectively, after about 1515 days (about 4.2 years). Although total Strategy A extraction is 265 gpm, the treatment facility can potentially treat up to 400 gpm (as described previously). If faster cleanup is desired, pumping from wells P1-P4 can be increased. Table 4 shows how the predicted time needed for cleanup decreases as P1-P4 pumping rates increase. Table 4 also shows the estimated present worth of operations and maintenance (O&M) costs for all strategies. (Appendix B contains cost estimation details.) Each strategy in Table 4 achieves plume capture as defined above.

Strategy A has the least annual operation and maintenance (O&M) costs. As described in Appendix B, the relationship between O&M costs and total pumping is approximately linear. Therefore, increasing total pumping increases annual O&M costs. However, as total pumping increases, the time needed to achieve cleanup goals decreases. These two factors make relationship between total pumping and present worth of costs very complex.

The pumping strategies remove contaminated water at different time-varying concentrations. As a result, treatment plant effluent concentrations vary with time. Table 4 shows the greatest plant effluent TCE concentration expected to result from the pumping strategies. These concentrations are the largest average concentrations simulated using 0.1 day time increments.

In Table 4, the present worth values depend on the estimated time needed for cleanup. Neither the time periods nor the concentrations are known with certainty because no transport model has been calibrated to the contaminant plumes. The applied transport models are not calibrated because of (1) lack of concentration data over time and (2) lack of accurate estimate of degradation or retardation (absorption) factors. Thus the values in Table 4 are derived using the transport models as estimates, assuming retardation but no degradation.

Figures 20-23 display Strategy A backtracks and capture zones for different plumes and model layers. Assuming no retardation, all pathlines take no more than 6 years to reach an extraction well⁵. The capture zones cover the specified target area. (Uncaptured southern parts of the plumes are farther south than the current capture zone and our target area defined in condition 1 above.) Figures 24-27 show the pathlines resulting from implementing pumping Strategy C.

Ideally, screens should be placed to extract the most contaminated water. Wells should extract as little clean water (concentrations less than 94 ppb TCE or 230 ppb DCE) as possible. Screen elevations recommended in Table 3 are based on the PES flow model. Actual screen elevations and pumping rates from individual layers may need to be adjusted during system installation and testing.

TABLE 3. Well locations and optimal pumping rates for strategy A.

Well	Easting (feet)	Northing (feet)	Primary Purpose(s)	Screen Interval (feet above MSL) ¹	Model Layer(s)	Pumping Rate (gpm) ^{2,3}
P1	2,253,391.44	413,128.69	Capture+cleanup	580-553	1, 2, and 3	90
P2	2,253,391.44	413,008.69	Capture+cleanup	580-553	1, 2, and 3	60
P3	2,253,751.44	413,188.69	Capture+cleanup	580-563	1, 2, and 3	40
P4	2,253,031.44	413,008.69	Cleanup	580-560	1 and 2	15
P5	2,254,231.44	413,068.69	Capture+cleanup	576-560	2	20
P6	2,254,531.44	413,428.69	Capture	576-560	2	20
P7	2,254,291.44	412,708.69	Capture	576-560	2	20

Notes:

1. Screen elevations are based on the modified flow model layers.
2. Pumping rates are rounded to the nearest 5 gpm.

³ Pathlines extend from the well backwards for up to six-years travel distance. Pathlines moving from a recharge source (such as precipitation) or from another layer might reach the well in less than six years.

TABLE 4. Alternative pumping strategies and time needed for cleanup.

Strategy	P1 (gpm)	P2 (gpm)	P3 (gpm)	P4 (gpm)	Total Extraction (gpm)	Time Needed for TCE&DCE Cleanup (Years)	Estimated Largest Treated Water Concentration (ppb)	Estimated Present Worth of O&M costs (\$)
A	90	60	40	15	265	4.1	1.4	803,585
B	110	70	50	20	310	3.6	2.2	827,872
C	115	80	50	25	330	3.3	3.0	817,269
D	125	85	55	25	350	3.1	3.7	848,212
E	135	90	60	25	370	3.0	4.4	847,387
F	150	100	60	30	400	2.7	5.0	850,014

Notes:

1. Total Extraction = sum of pumping from P1-P4 plus sum of pumping from P5-P7 (60 gpm).
2. Estimated largest treated water concentration is based on the largest average pumped water concentration during the time needed for cleanup and the treatment facility's removal efficiency (Table 2).

5.1. Sensitivity Analysis

Sensitivity analysis predicts that even if field transmissivities are 50% higher or 50% lower than those in the calibrated flow model, the pumping rates for all strategies shown in Table 4 will adequately capture the TCE and DCE plumes. The presented strategies are sufficiently robust to capture the plumes even if the model predictions are somewhat inaccurate.

To illustrate the modeled capture zones in Figures 28-31, we employ the Strategy A capture zones in all model layers when transmissivities are reduced by 50%. We also show Strategy A capture zones in all model layers when transmissivities are increased by 50% in Figures 32-35. We show strategy A because it has the lowest total extraction. Therefore, it is the strategy least robust (most sensitive) to changes in transmissivity. Figures 32 and 34 show the areas of the TCE and DCE plumes that are most sensitive to changes in transmissivity. These areas should be monitored closely.

6. SUMMARY AND RECOMMENDATIONS

To provide WAFB a range of alternatives, we present six pumping strategies. All strategies require less than 400 gpm of total extraction. Based on manufacturer guidance and assuming the average TCE concentration of extracted water does not exceed 400 ppm, the existing treatment facility should be able to reduce the concentration of a 400 gpm flow to 5 ppb TCE. Each strategy is sufficiently robust to capture the plumes even if the model predictions are somewhat inaccurate. That is, even if hydraulic conductivity values are reduced or increased by 50%.

Continued monitoring of concentrations is required to assure cleanup and capture, especially before the extraction wells are turned off. It is important to monitor the areas shown in Figures 32 and 34 to assure capture of the TCE and DCE plumes.

Table 4 shows that Strategy A has the lowest O&M costs. However, Strategy C costs are only 1.7% greater and Strategy C requires approximately one less year to achieve cleanup. Assuming, its treated water concentrations are acceptable, we recommend Strategy C for implementation by WAFB.

One the other hand, if treated water concentration should not exceed 1.5 ppb, Strategy A is preferred. Depending on actual treated water concentrations, WAFB can vary the pumping rates for wells P4-P7 between the values of Strategies A and C. Although this would require real-time management of the P&T operation, it can significantly speed cleanup.

7. REFERENCES

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APPENDIX A. Background for Pumping Strategy Development

The pumping strategy design approach involves two consecutive steps: (1) developing a cleanup pumping strategy based upon one of the below formulations, and (2) developing a pumping strategy that minimizes the additional pumping (beyond that of the cleanup strategy) needed to achieve capture. In the following discussion, CMAX is the greatest concentration that will remain in the aquifer after six years of pumping. For the first step, USU considered the following

Formulation 1:

Minimize: PW = present worth of P&T costs (installation, pumping, and treatment)
Subject To: $CMAX_{TCE} \leq 94$ ppb
 $CMAX_{DCE} \leq 230$ ppb
Enough capacity (of a 400 gpm total) remains for capture

Formulation 2:

Maximize: TCE Mass Removed
Maximize: DCE Mass Removed
Subject to: $CMAX_{TCE} \leq 94$ ppb
 $CMAX_{DCE} \leq 230$ ppb
Enough capacity (of a 400 gpm total) remains for capture

Formulation 3:

Minimize: $CMAX_{TCE}$
Minimize: $CMAX_{DCE}$
Subject to: $CMAX_{TCE} \leq 94$ ppb
 $CMAX_{DCE} \leq 230$ ppb
Enough capacity (of a 400 gpm total) remains for capture

Formulation 4:

Maximize: TCE Mass Removed
Subject to: $CMAX_{TCE} \leq 94$ ppb
 $CMAX_{DCE} \leq 230$ ppb
Enough capacity (of a 400 gpm total) remains for capture

Formulation 5:

Minimize: $CMAX_{TCE}$
Subject to: $CMAX_{TCE} \leq 94$ ppb
 $CMAX_{DCE} \leq 230$ ppb
Enough capacity (of a 400 gpm total) remains for capture

Discussion:

Formulation 1 was discarded for the following reason. Treatment costs are much greater than well installation and pumping costs combined. This means that minimizing total cost is equivalent to minimizing total pumping. Such a design will pump no more than needed to reduce the TCE concentrations to 94-ppb TCE by the end of 6 years. This provides no safeguard against simulation model inaccuracy. No transport model has been calibrated for this site. The applied transport model does not assume degradation. Such a model should be used with care and with a safety factor.

Formulations 2 and 3 were discarded because they were multi-objective. A multi-objective design requires defining criteria that reflect the relative importance of the different objectives. Such criteria are based on preferences and judgement. Thorough evaluation requires developing a tradeoff curve to reflect preferences. That effort was beyond the scope of this project.

Formulations 4 and 5 focus on TCE cleanup. It was not known apriori which formulation will provide a superior design. The following preliminary results help contrast the application of Formulations 4 and 5 for our problem.

Preliminary Results:

Initially five hundred systematic flow and transport simulations were performed to obtain an idea of how final concentrations would respond to a range of pumping strategies. All simulations assumed a total pumping of 180 gpm. (The pumping strategy developed in October 1996 required 220 gpm of extraction to achieve capture. Assuming a 400 gpm maximum total extraction, 180 gpm was assumed available for cleanup.) Simulations considered different pumping strategies for a set of 24 wells. No optimization was utilized in this step.

Table A1 shows the pumping strategy (simulation No. 131) that best achieved the goals of Formulation 4. The resulting $C_{MAX_{TCE}}$ is 88 ppb. Table A2 shows the pumping rates (simulation No. 376) that best achieved the goals of Formulation 5. The resulting $C_{MAX_{TCE}}$ is 80 ppb, only slightly better than that of the previous strategy (simulation No. 131). This pumping strategy extracts about 20% less total TCE mass than the previous strategy (Table A1).

Table A1. Pumping rates for simulation 131

Layer	Easting (ft)	Northing (ft)	P. Rate (gpm)
1	2,253,391.44	413,128.69	30
1	2,252,971.44	413,008.69	30
1	2,253,391.44	413,008.69	40
2	2,253,391.44	413,128.69	25
2	2,253,031.44	413,008.69	25
3	2,253,391.44	413,128.69	30
			180

Table A2. Pumping rates for simulation 376

Layer	Easting (ft)	Northing (ft)	P. Rate (gpm)
1	2,253,391.44	413,128.69	30
1	2,252,971.44	413,008.69	30
1	2,253,031.44	413,008.69	40
2	2,253,031.44	413,008.69	40
2	225,339,1.44	413,008.69	40
			180

Both strategies use the same total pumping (180 gpm) and both employ four wells -- four unique (row,column) locations. Both strategies yield $C_{MAX_{TCE}}$ below 94 ppb. Both strategies also yield $C_{MAX_{DCE}}$ below 230 ppb, suggesting we can emphasize TCE alone during cleanup strategy design.

Based on the above results and the uncertainty of predicted concentrations, it is preferable to emphasize maximizing the TCE mass removal rather than trying to achieve the lowest possible TCE concentration within six years. Accordingly, we chose to employ Formulation 4 for subsequent pumping strategy development.

APPENDIX B. Operations and Maintenance Costs Estimation

Our economic evaluation does not include the capital cost of pumping system installation for the following reasons. We use the same number of wells in all presented strategies. We consider any pump cost differences (due to different individual well pumping rates) insignificant. We cannot reasonably estimate conveyance system costs. (We do not expect these costs to vary significantly for proposed strategies.) Therefore we only consider O&M costs. We assume a discount rate of 5% to estimate present worth of costs. To estimate annual O&M costs, we use the same unit costs used by ICF in their feasibility study (ICF, 1996). The costs are as follow:

1. Pumping Costs: These costs are based on 5-hp pumps working continuously (24 hrs/day, 365 days/yr) and a unit electrical cost of \$0.09/kW-Hr obtained from Consumer's Power. Assume an 80% pump efficiency, annual pumping cost for each well is $\$2.066 PH$. Here, P is pumping rate in gpm and H is hydraulic lift in ft. To determine H , we used steady state heads just outside an assumed 6-inch well casing.
2. Treatment Costs: These costs are based on the current cost estimate for operating the Mission Drive treatment plant. Approximately, \$135,000 are spent annually and the current output of the plant is about 200 gpm (105,000,000 gallons per year). Therefore the treatment cost is $\$683.3 Q$, where Q is total extraction rate in gpm.

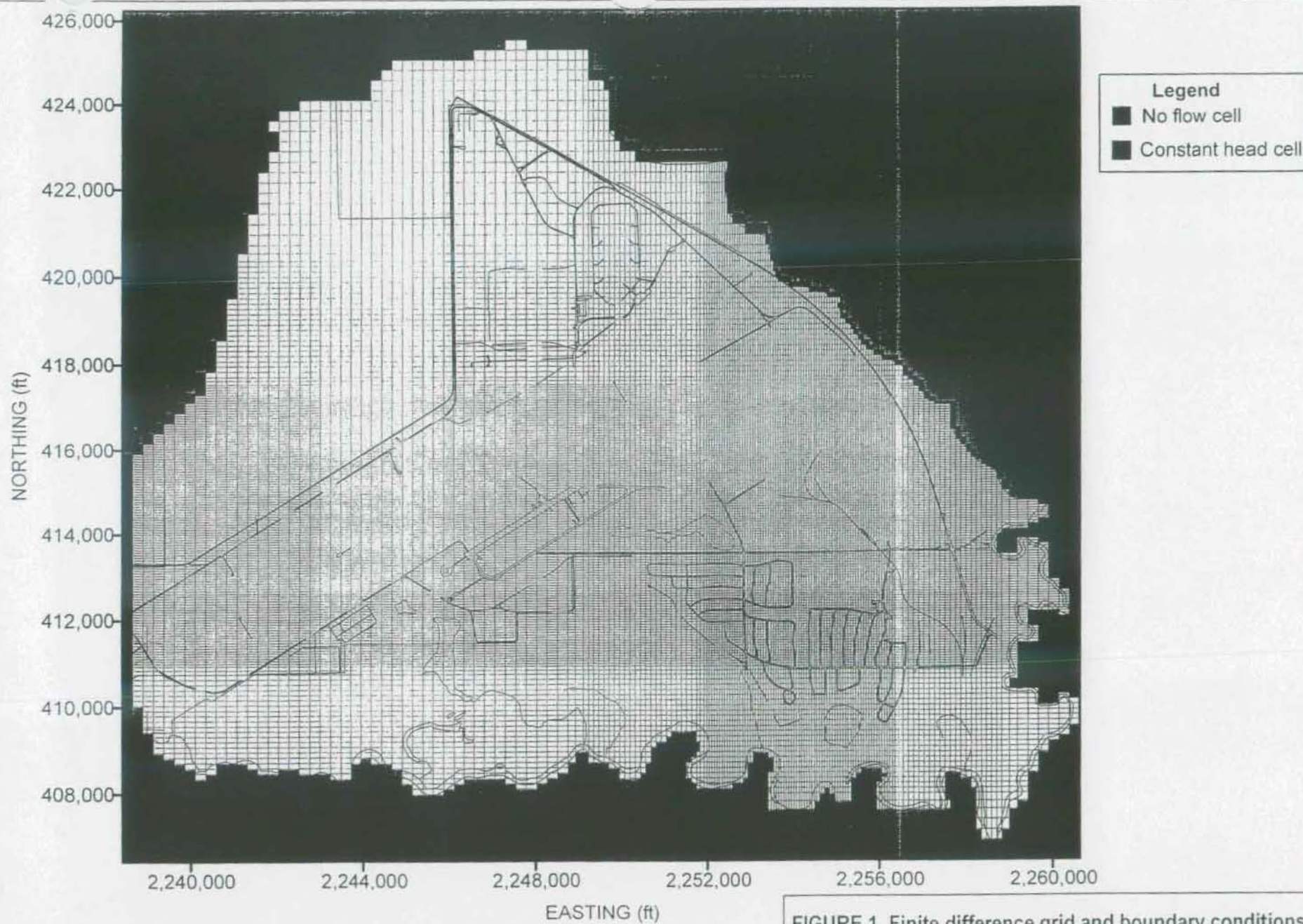


FIGURE 1. Finite difference grid and boundary conditions for the modified flow model, Wurtsmith AFB, Michigan.

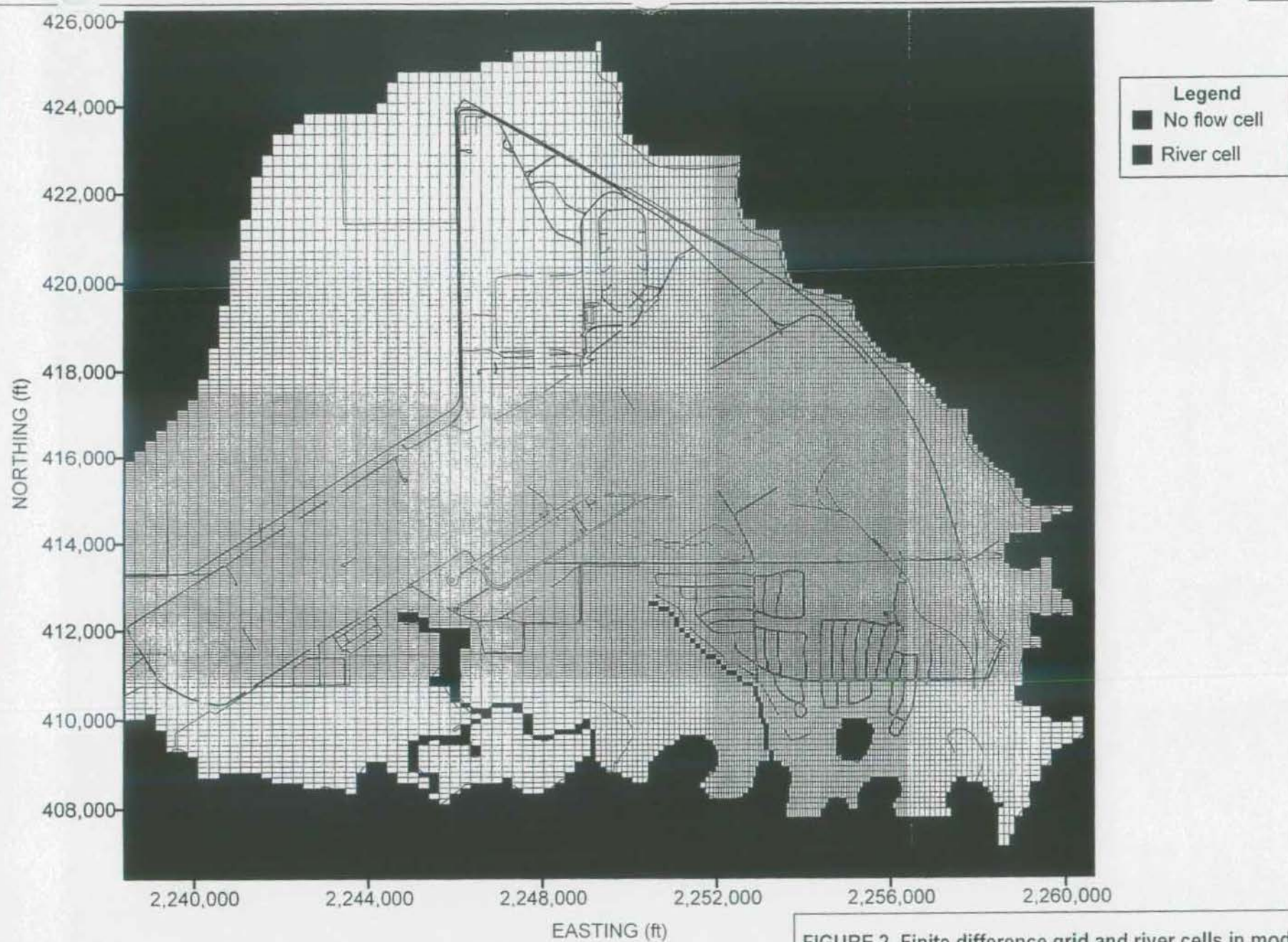


FIGURE 2. Finite difference grid and river cells in model layer 1 for the modified flow model, Wurtsmith AFB, Michigan.

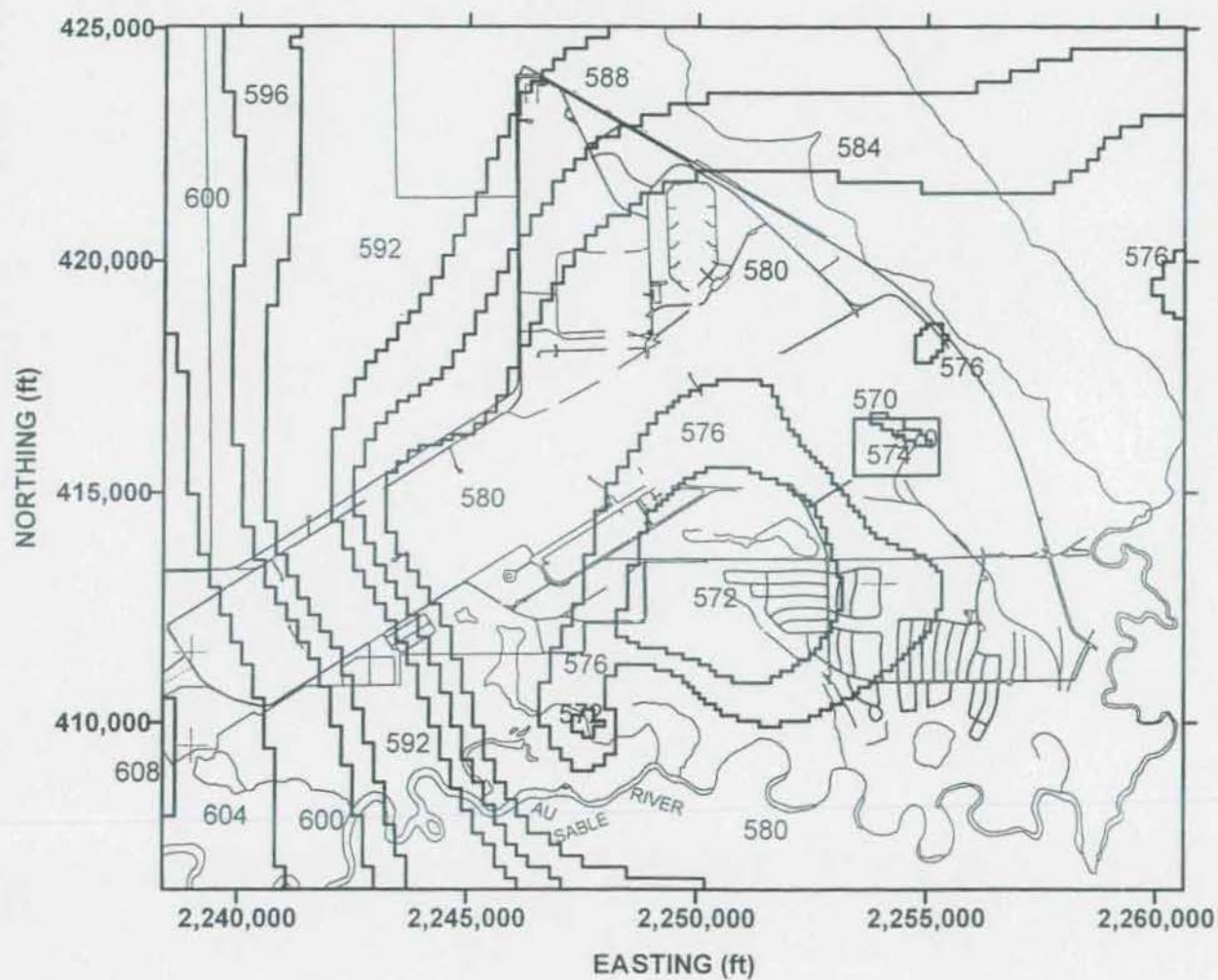


FIGURE 3. Bottom elevations for model layer 1 (ft above MSL), Wurstmith AFB, Michigan.

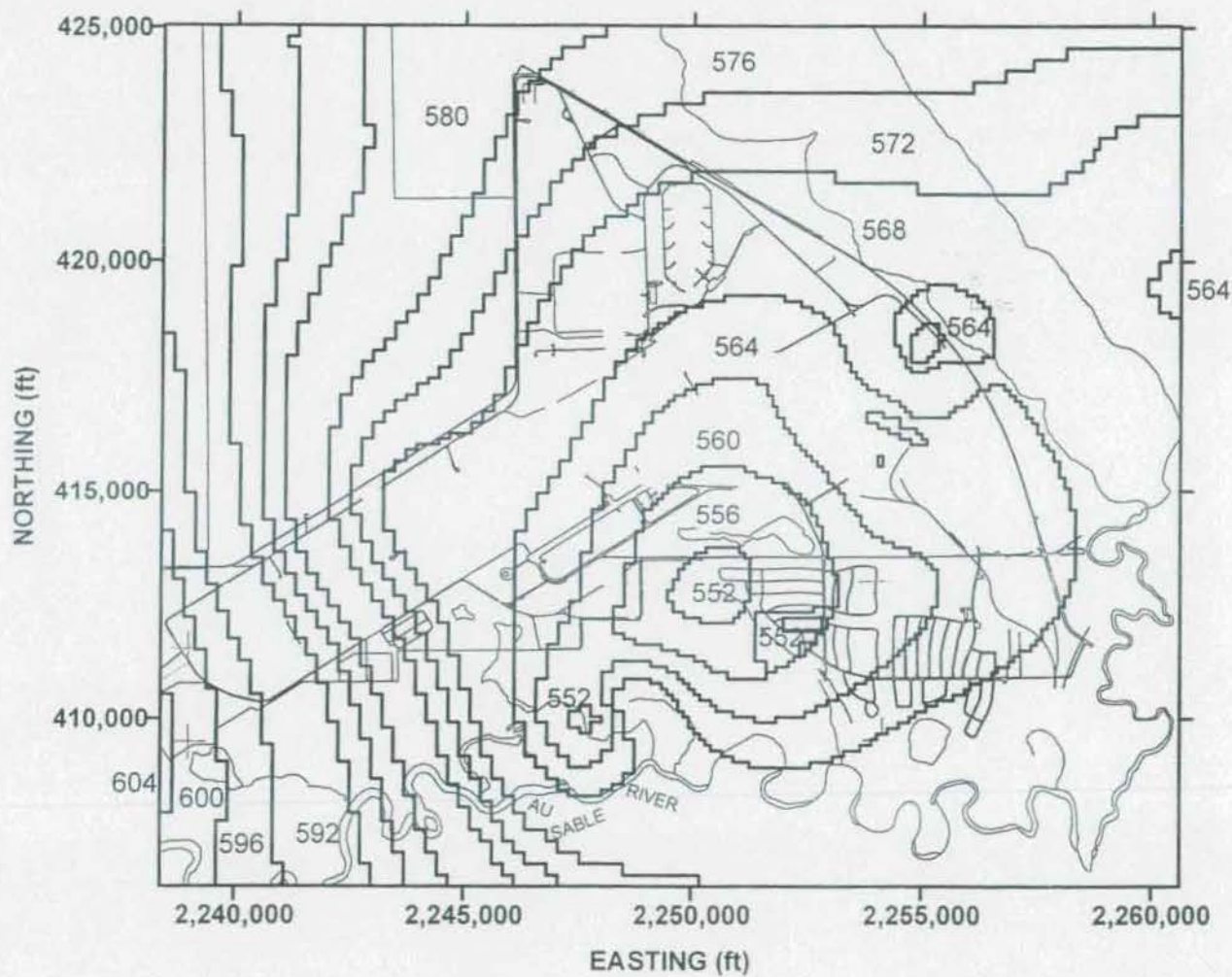


FIGURE 4. Bottom elevations for model layer 2 (ft above MSL), Wurstmith AFB, Michigan.

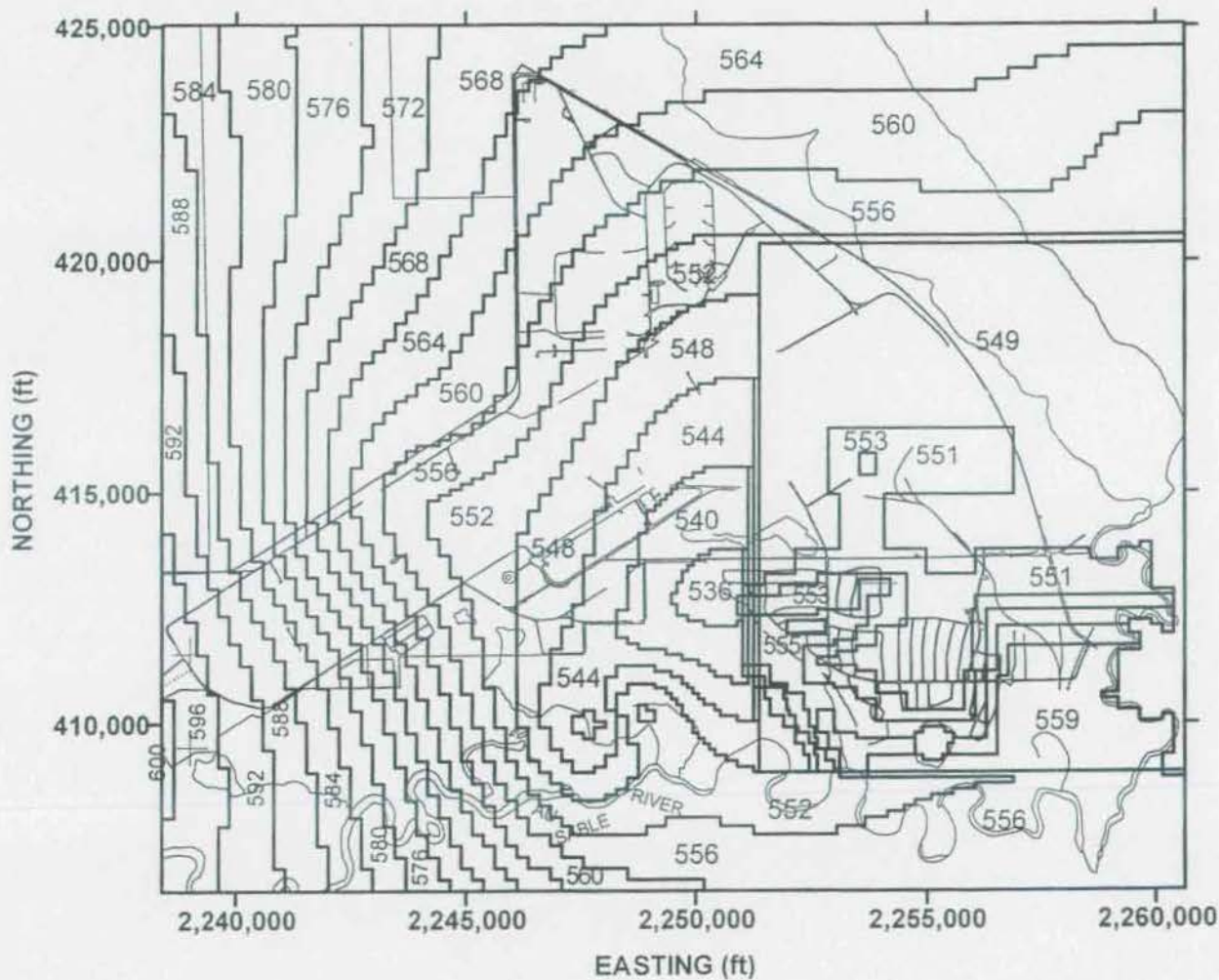


FIGURE 5. Bottom elevations for model layer 3 (ft above MSL), Wurstmith AFB, Michigan.

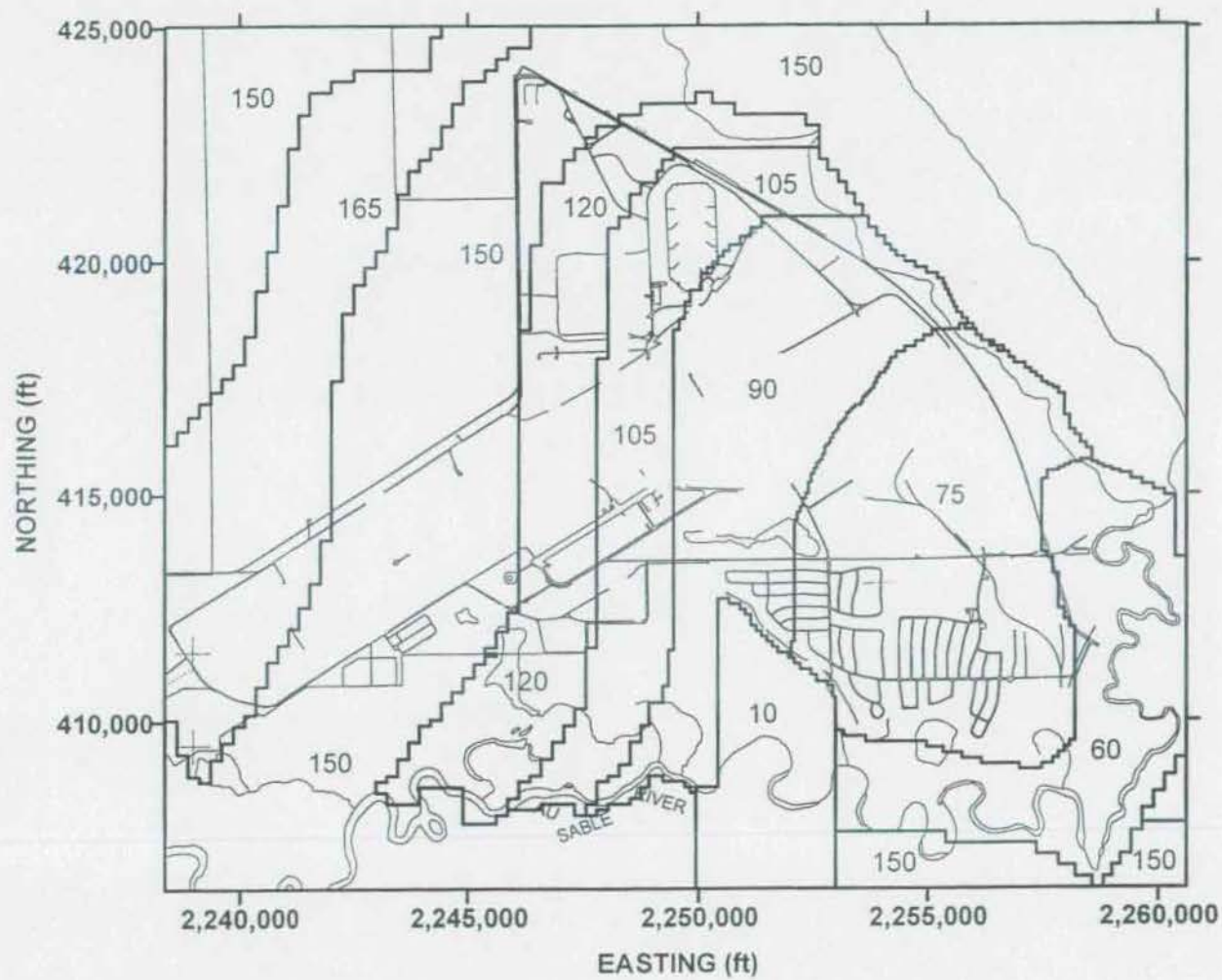


FIGURE 6. Hydraulic conductivity values in model layer 1 (ft/day), Wurtsmith AFB, Michigan.

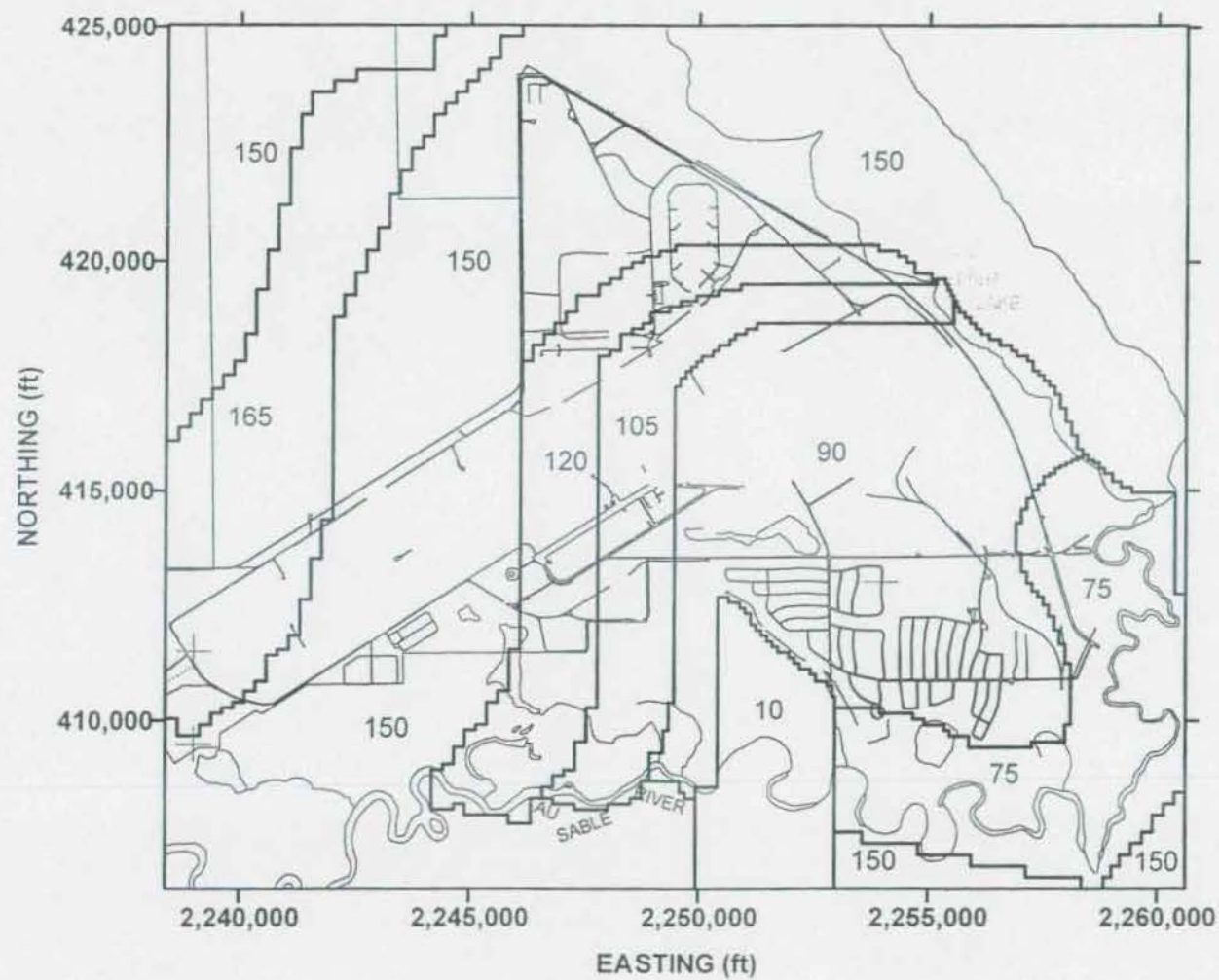


FIGURE 7. Hydraulic conductivity values in model layer 2 (ft/day), Wurstmith AFB, Michigan.

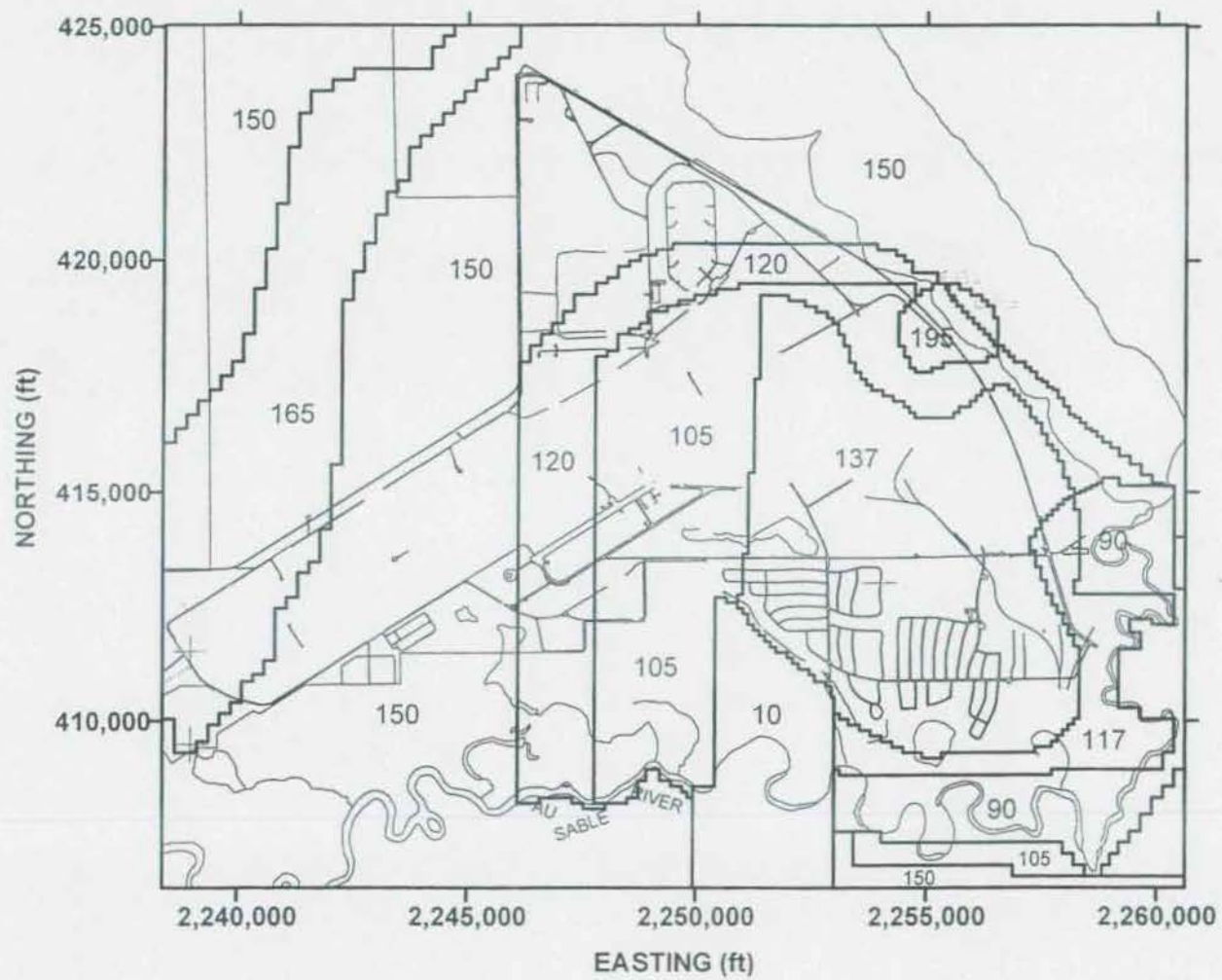


FIGURE 8. Hydraulic conductivity values in model layer 3 (ft/day), Wurstmith AFB, Michigan.

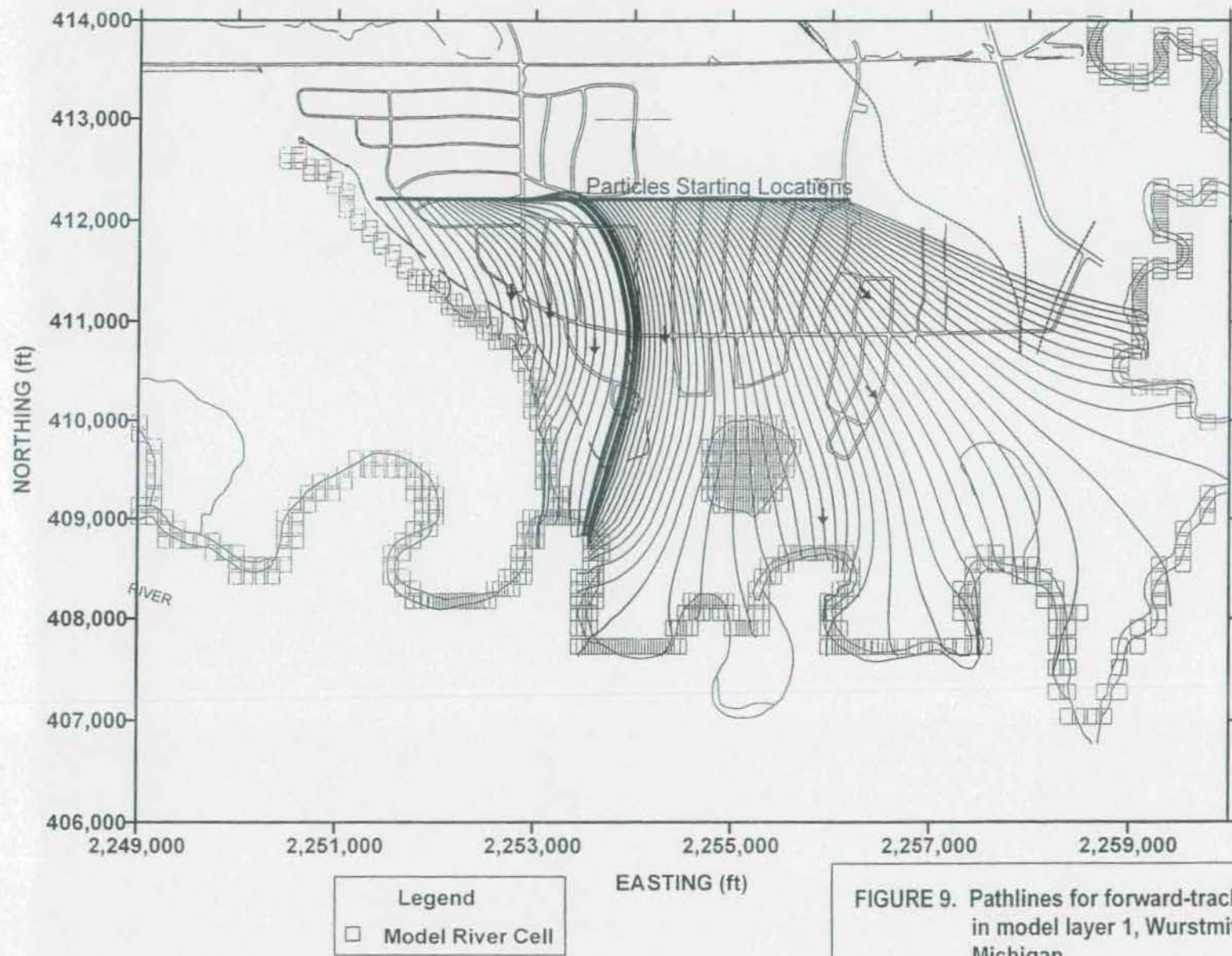


FIGURE 9. Pathlines for forward-tracked particles in model layer 1, Wurstmith AFB, Michigan.

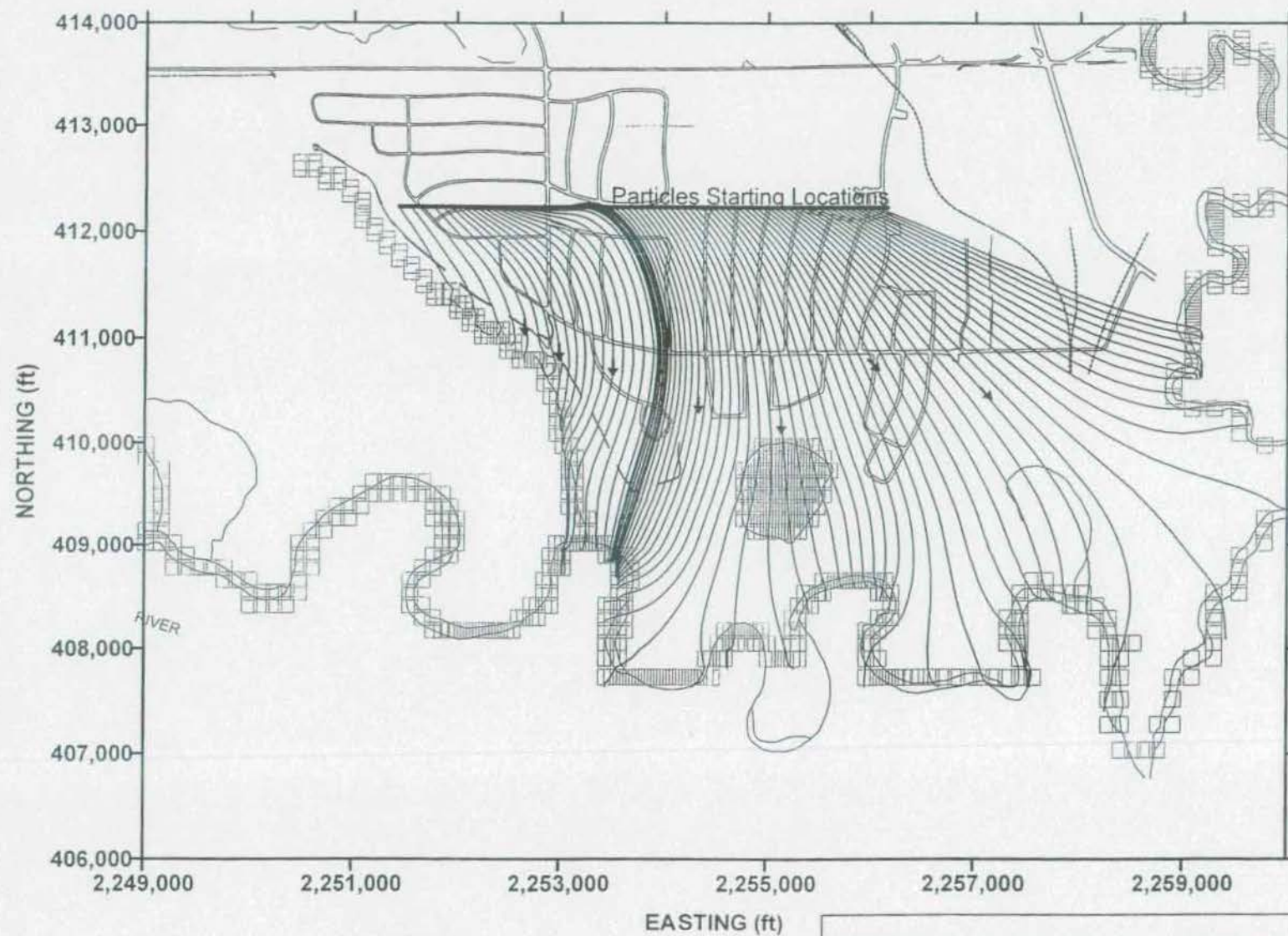


FIGURE 10. Pathlines for forward-tracked particles in model layer 2, Wurstmith AFB, Michigan.

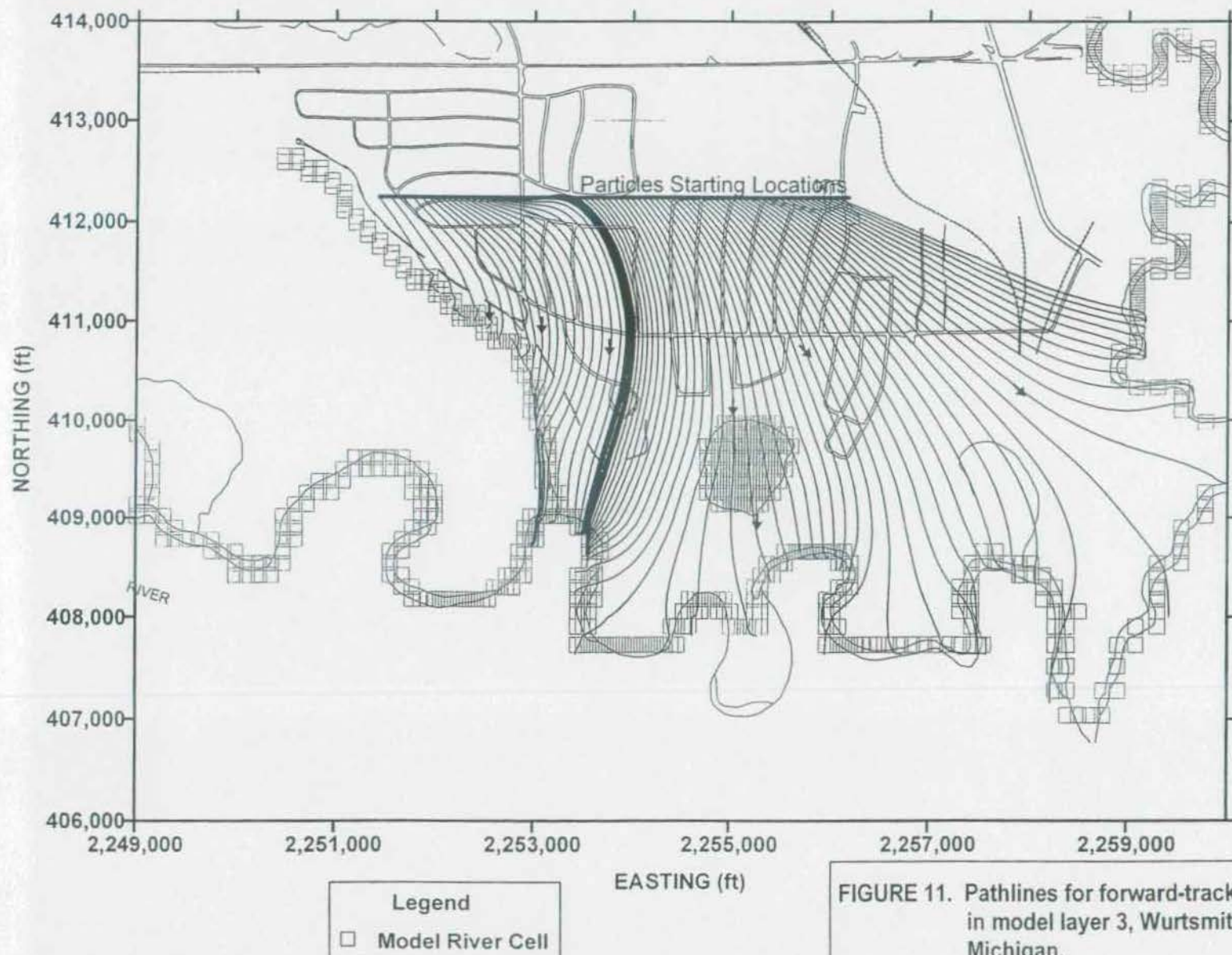


FIGURE 11. Pathlines for forward-tracked particles in model layer 3, Wurtsmith AFB, Michigan.

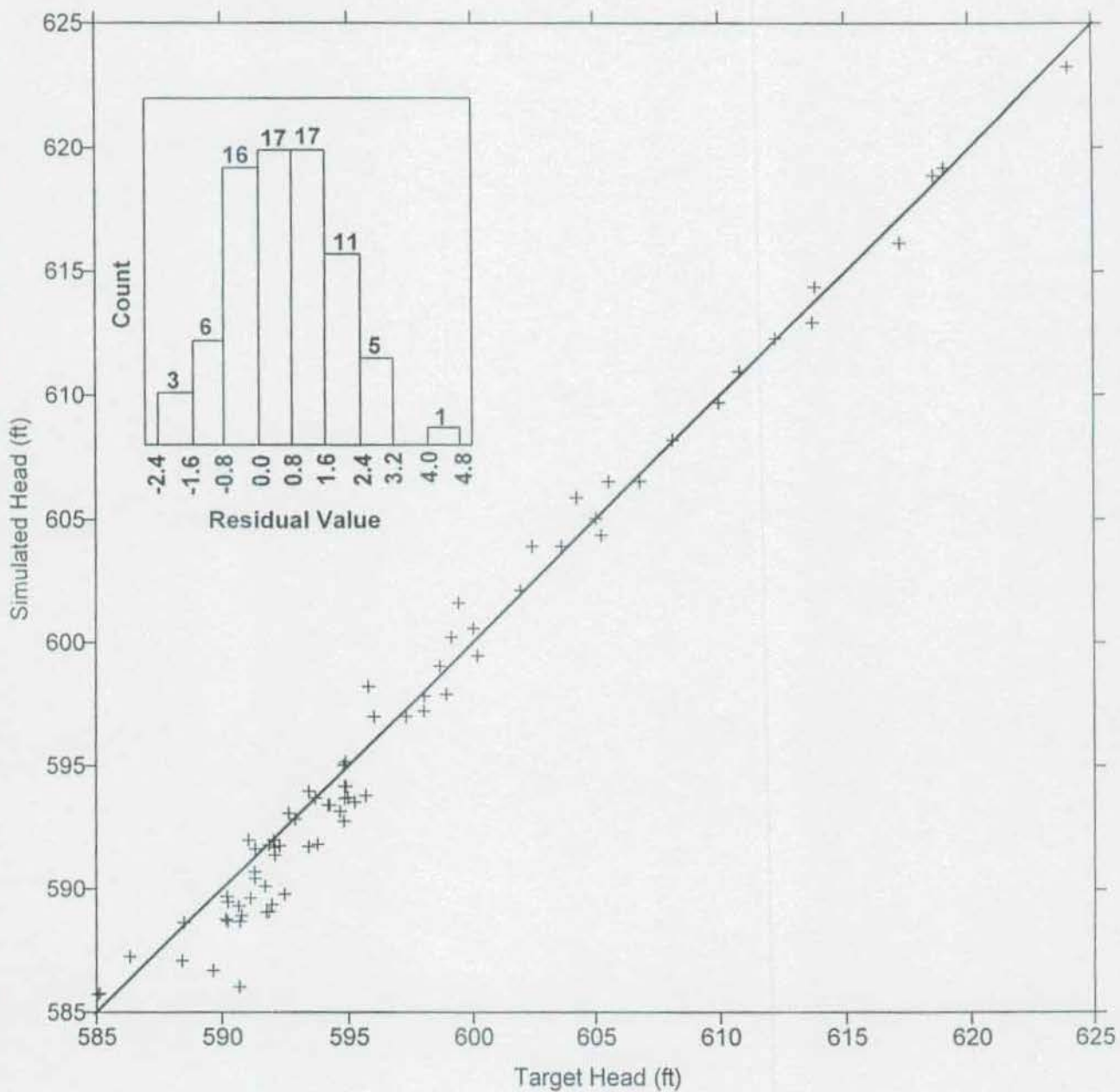


FIGURE 12. Simulated versus target head values and histogram of residuals for modified MODFLOW model, Wurstmith AFB, Michigan.

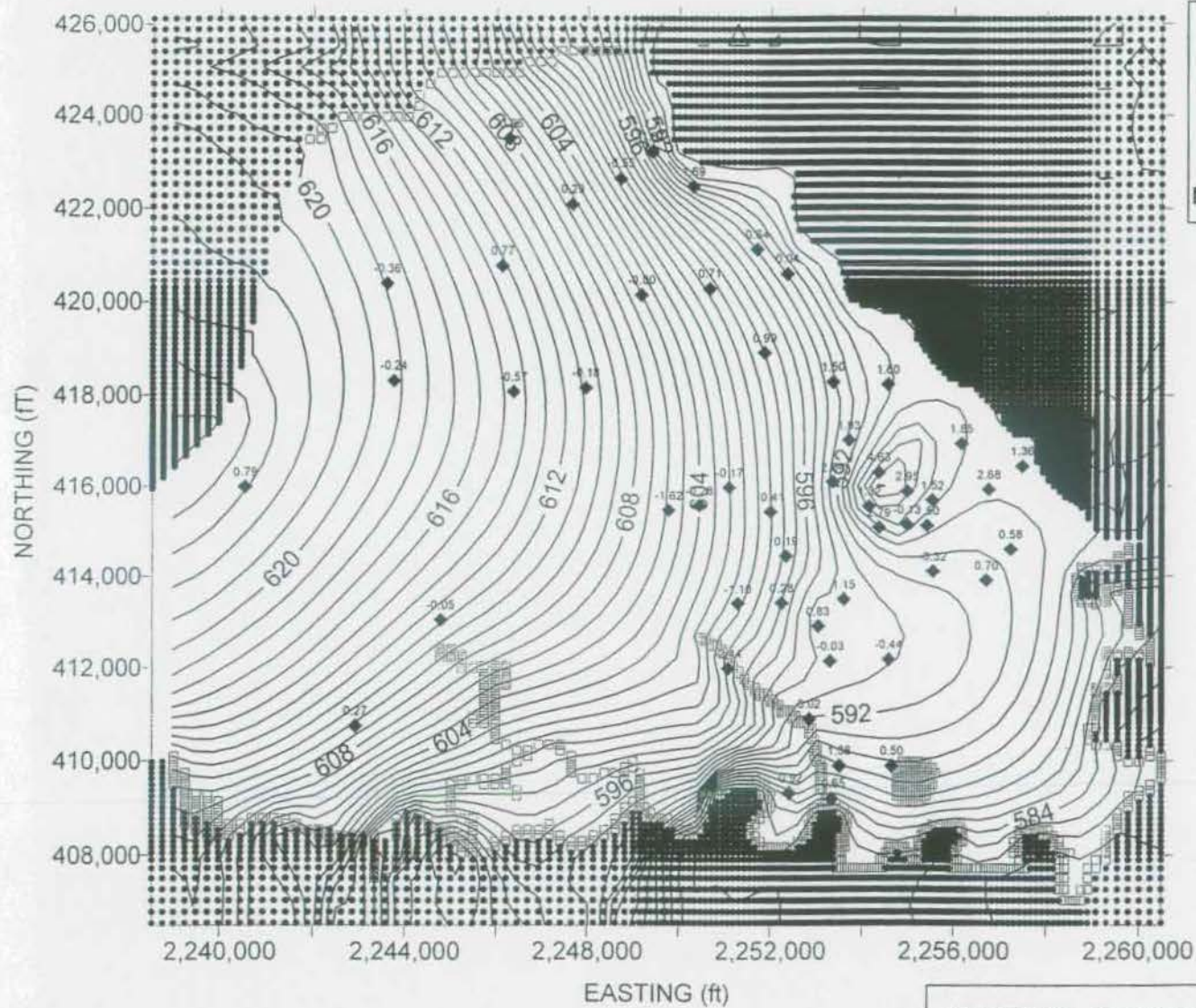


FIGURE 13. Simulated steady-state heads and residuals (in feet) for model layer 1, Wurstmith AFB, Michigan.

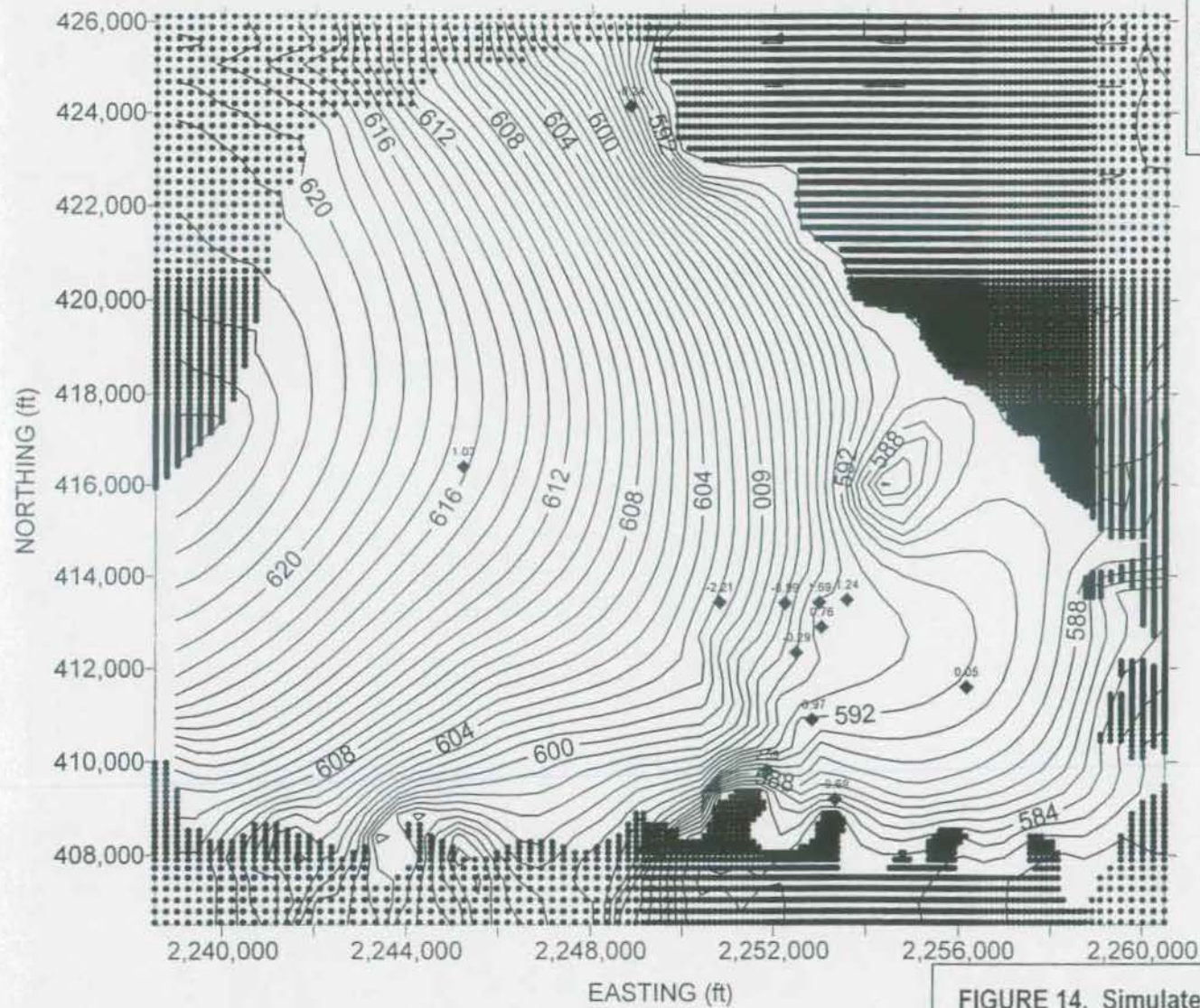


FIGURE 14. Simulated steady-state heads and residuals (in feet) for model layer 2, Wurstmith AFB, Michigan.

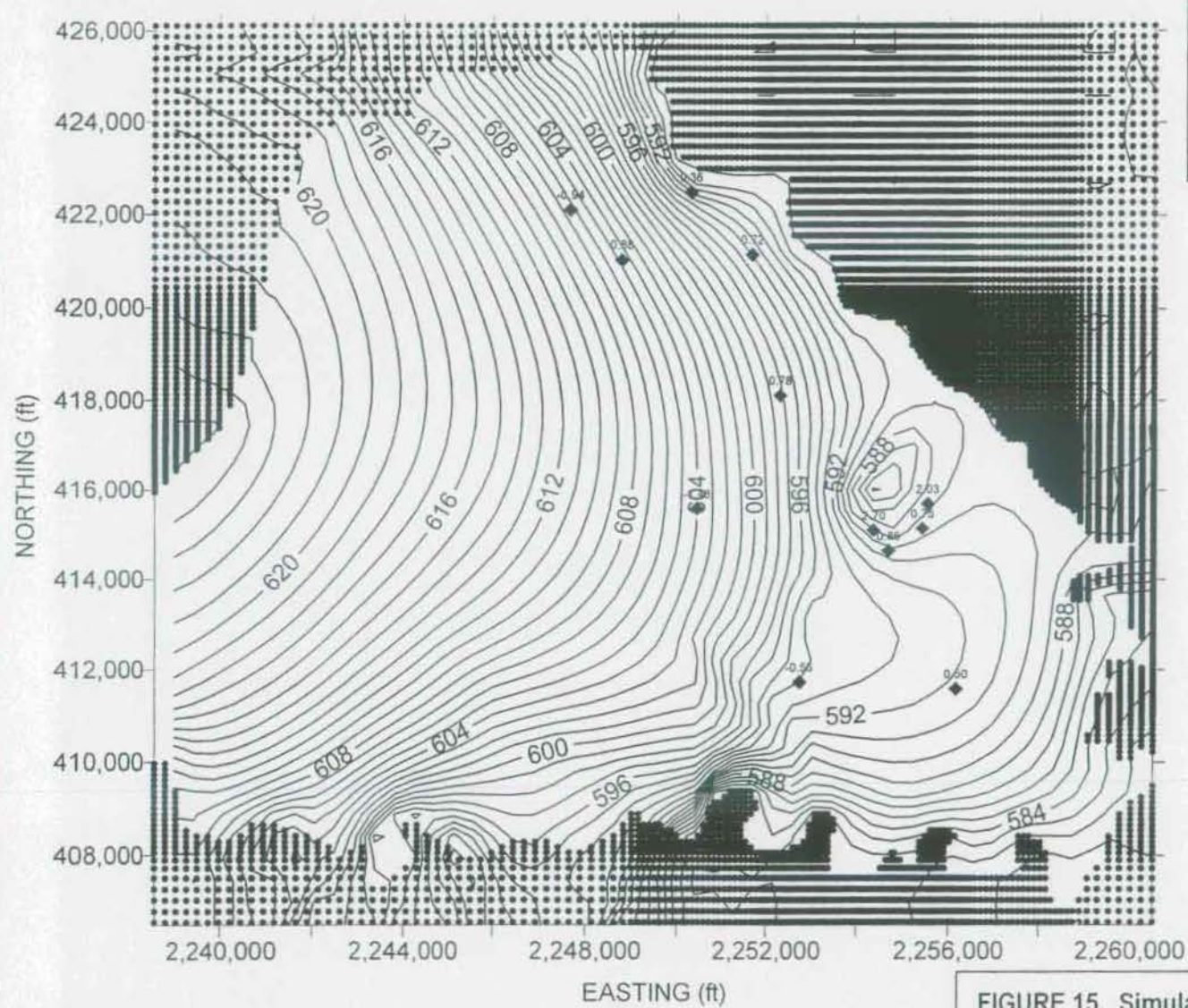
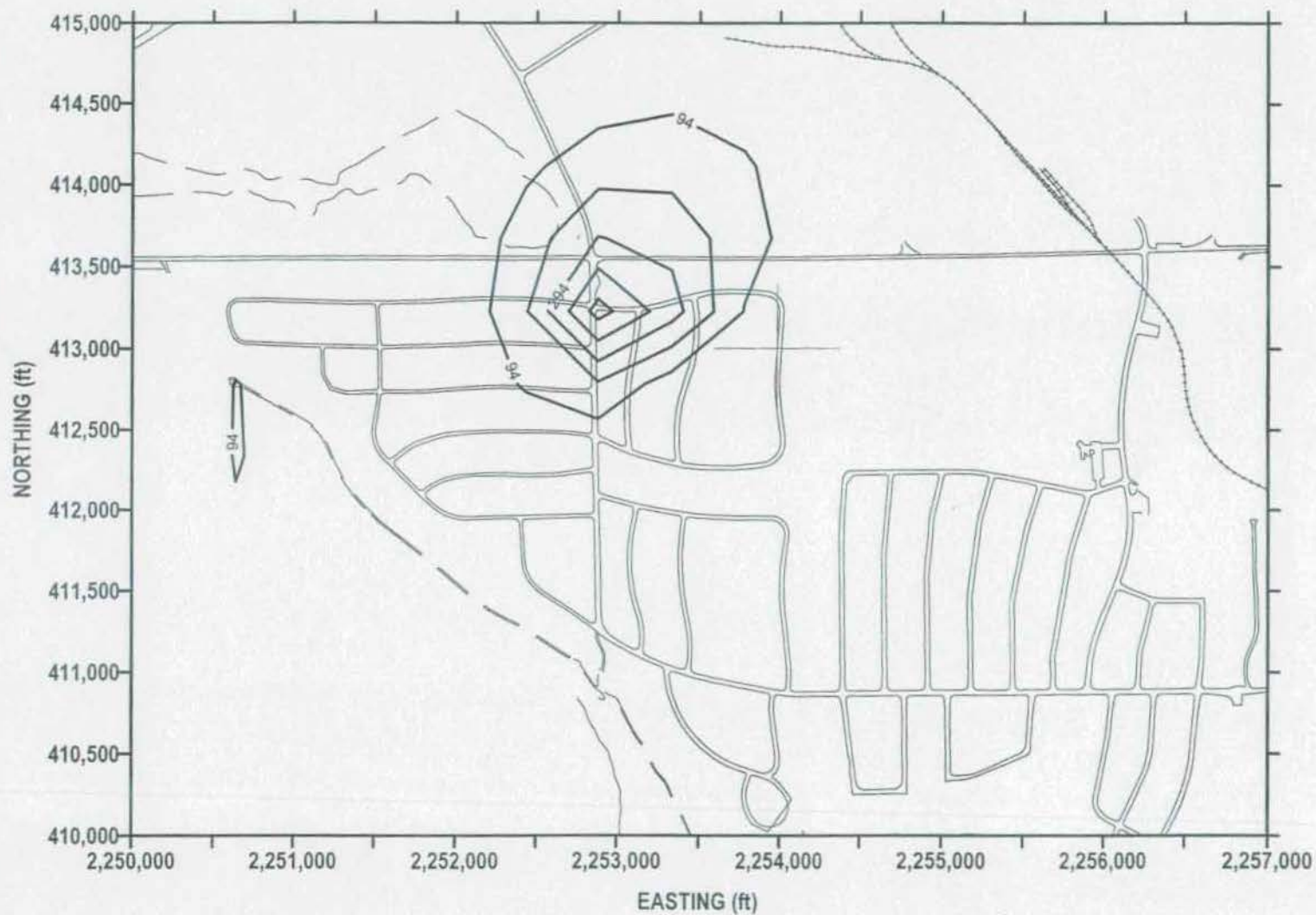


FIGURE 15. Simulated steady-state heads and residuals (in feet) for model layer 3, Wurstmith AFB, Michigan.



Legend
Contour interval 100 ppb

FIGURE 16. Initial TCE concentrations in model layer 1, Wurtsmith AFB, Michigan.

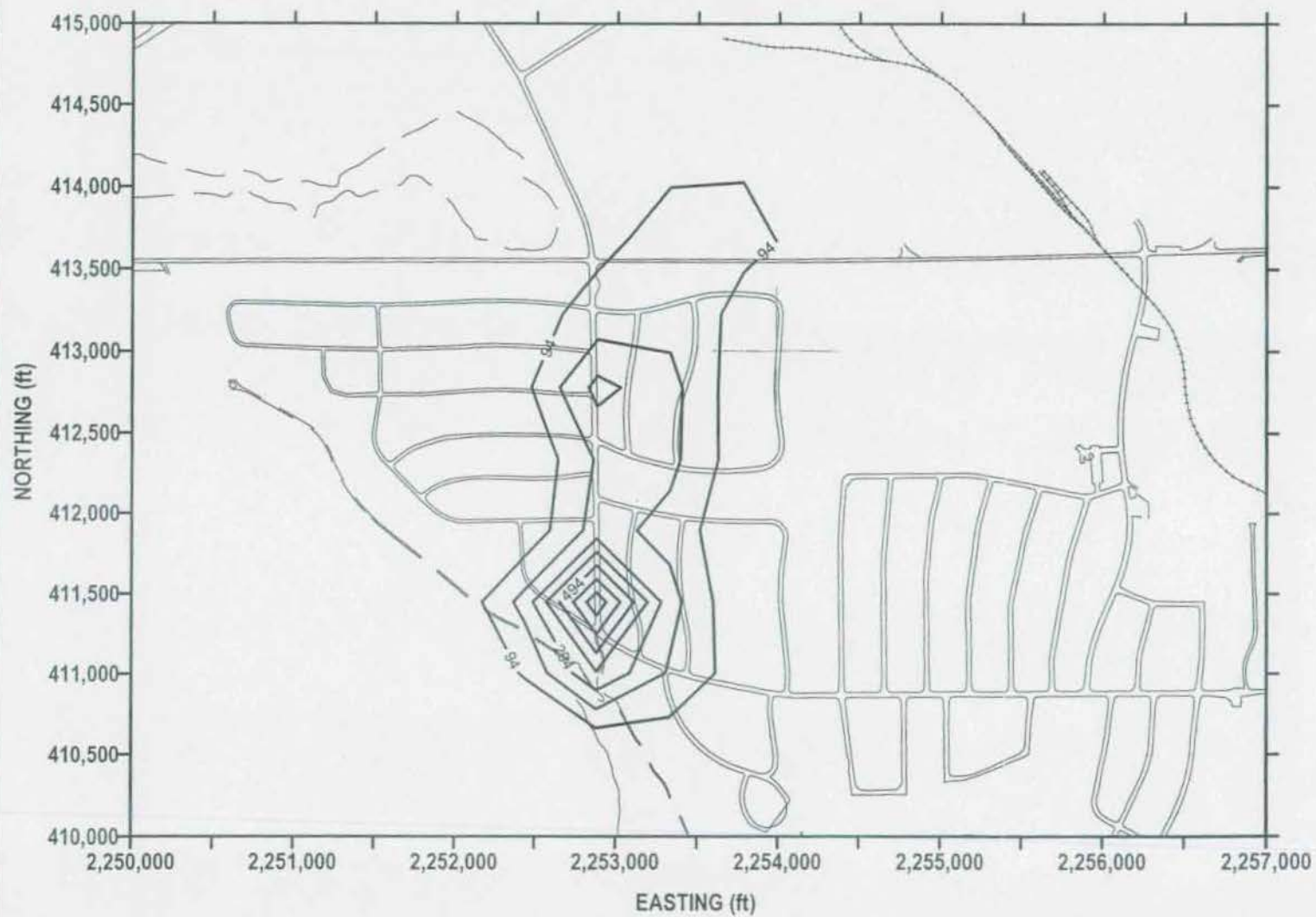
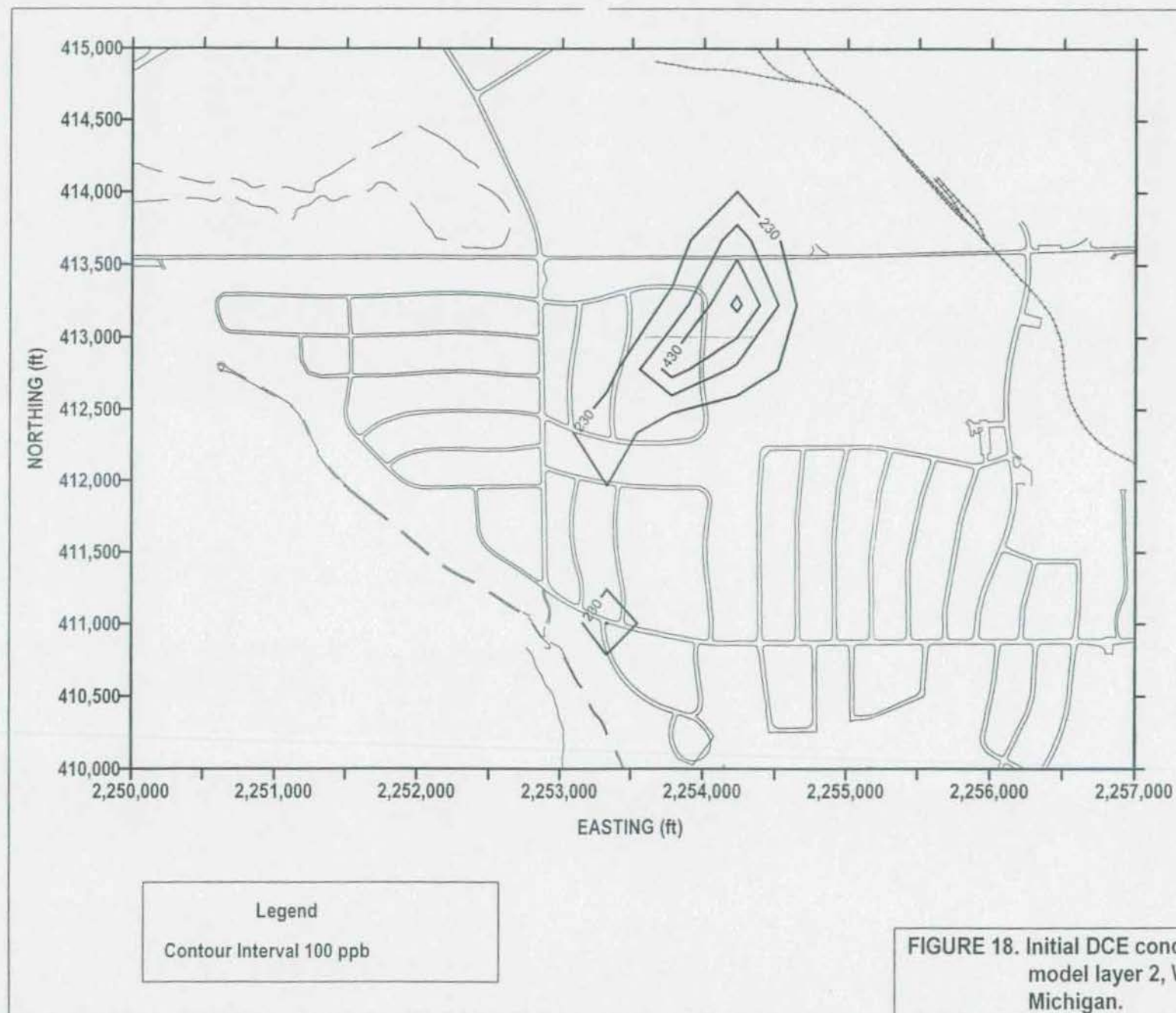
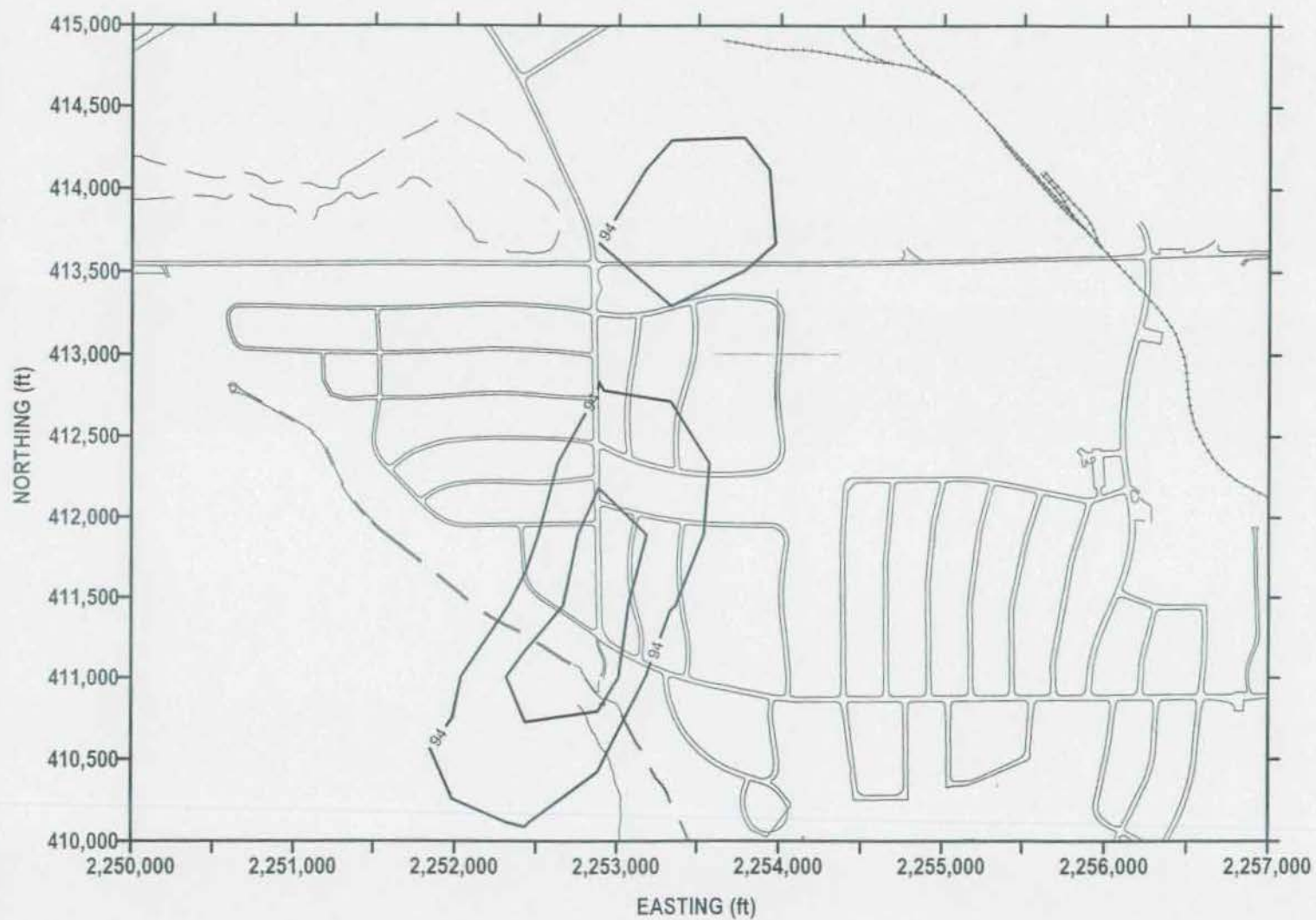


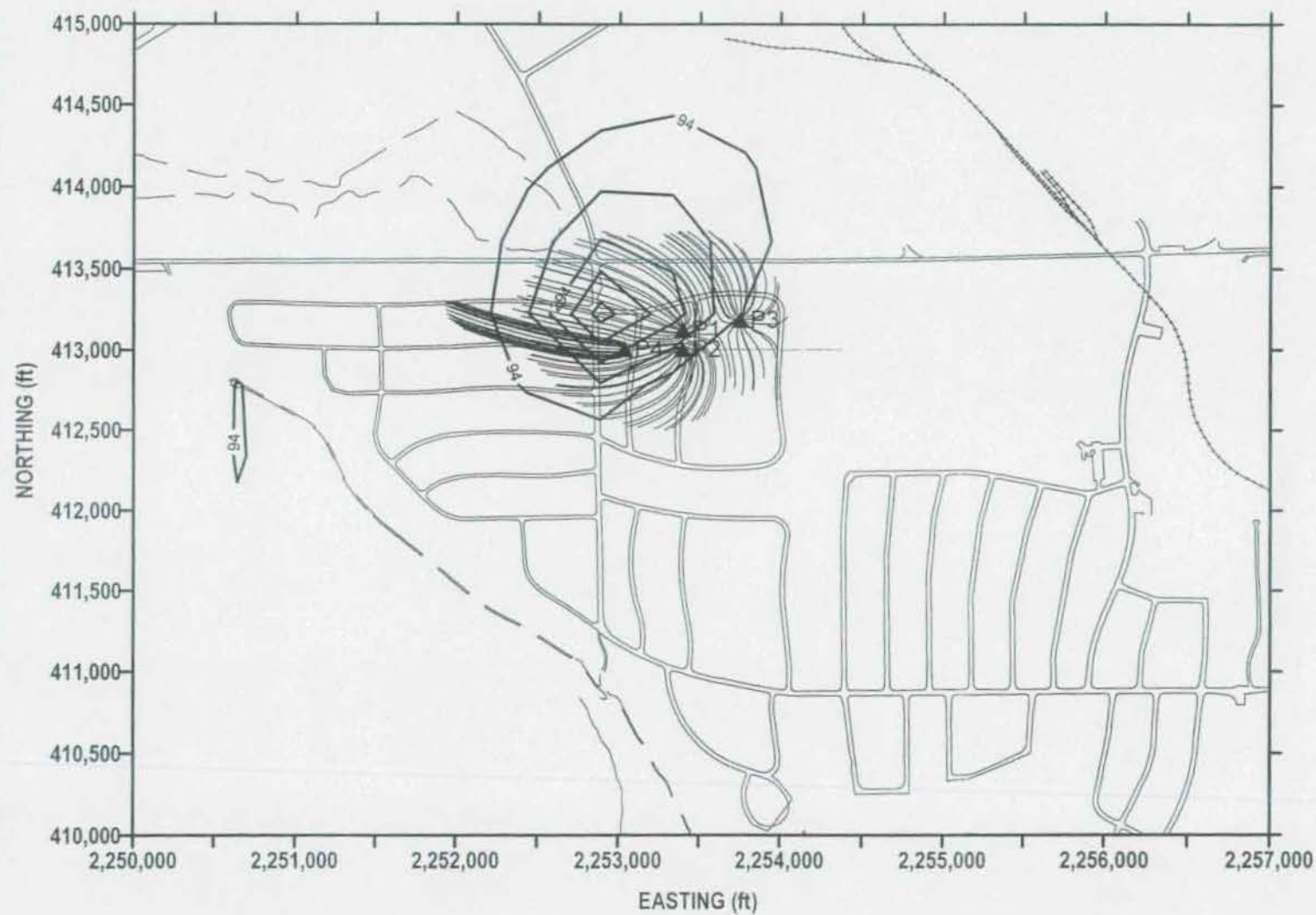
FIGURE 17. Initial TCE concentrations in model layer 2, Wurtsmith AFB, Michigan.





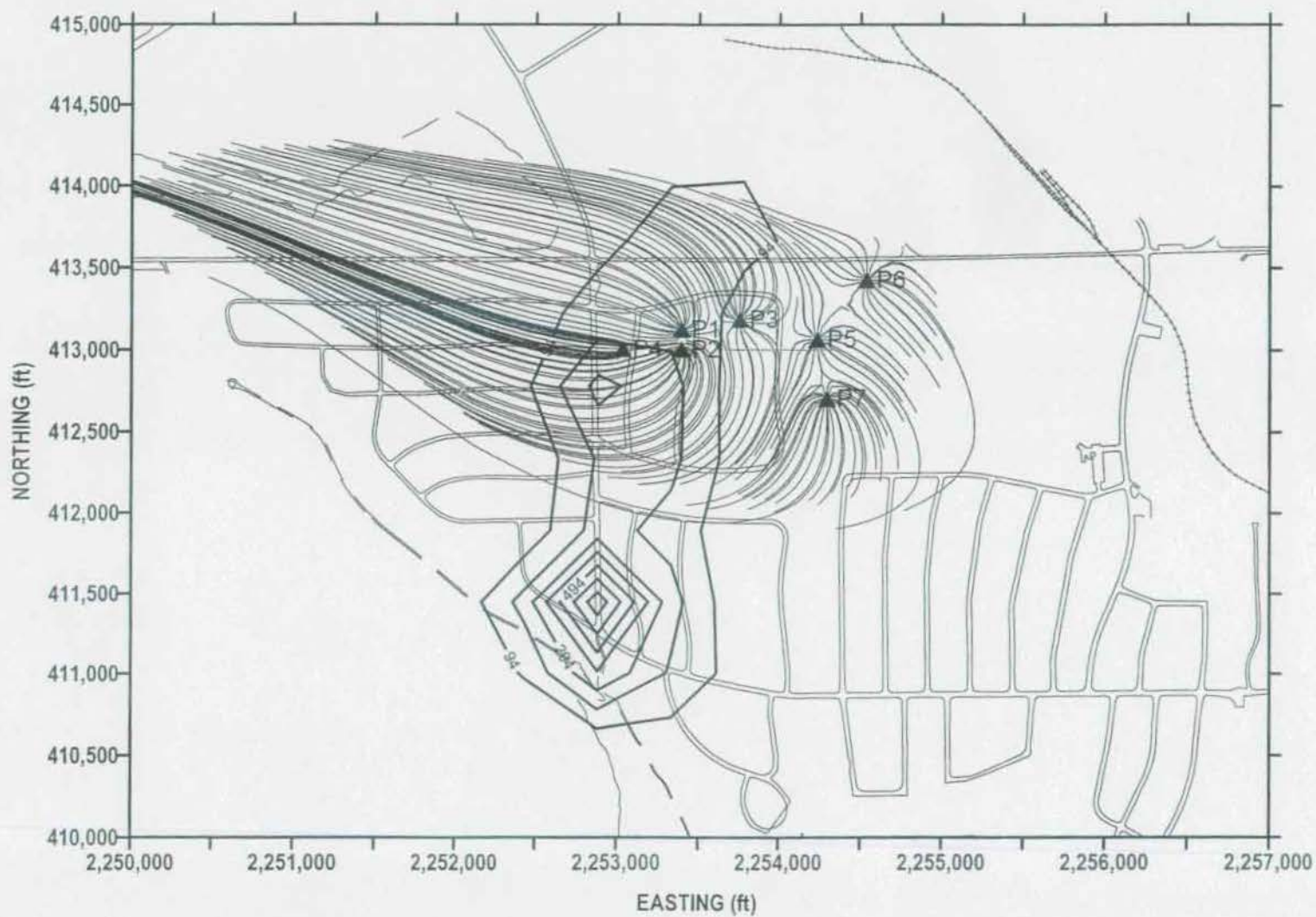
Legend
Contour Interval 100 ppb

FIGURE 19. Initial TCE concentrations in model layer 3, Wurtsmith AFB, Michigan.



Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 20. Initial TCE concentrations in model layer 1 and pathlines resulting from pumping strategy A, Wurtsmith AFB, Michigan.



Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 21. Initial TCE concentrations in model layer 2 and pathlines resulting from pumping strategy A, Wurtsmith AFB, Michigan.

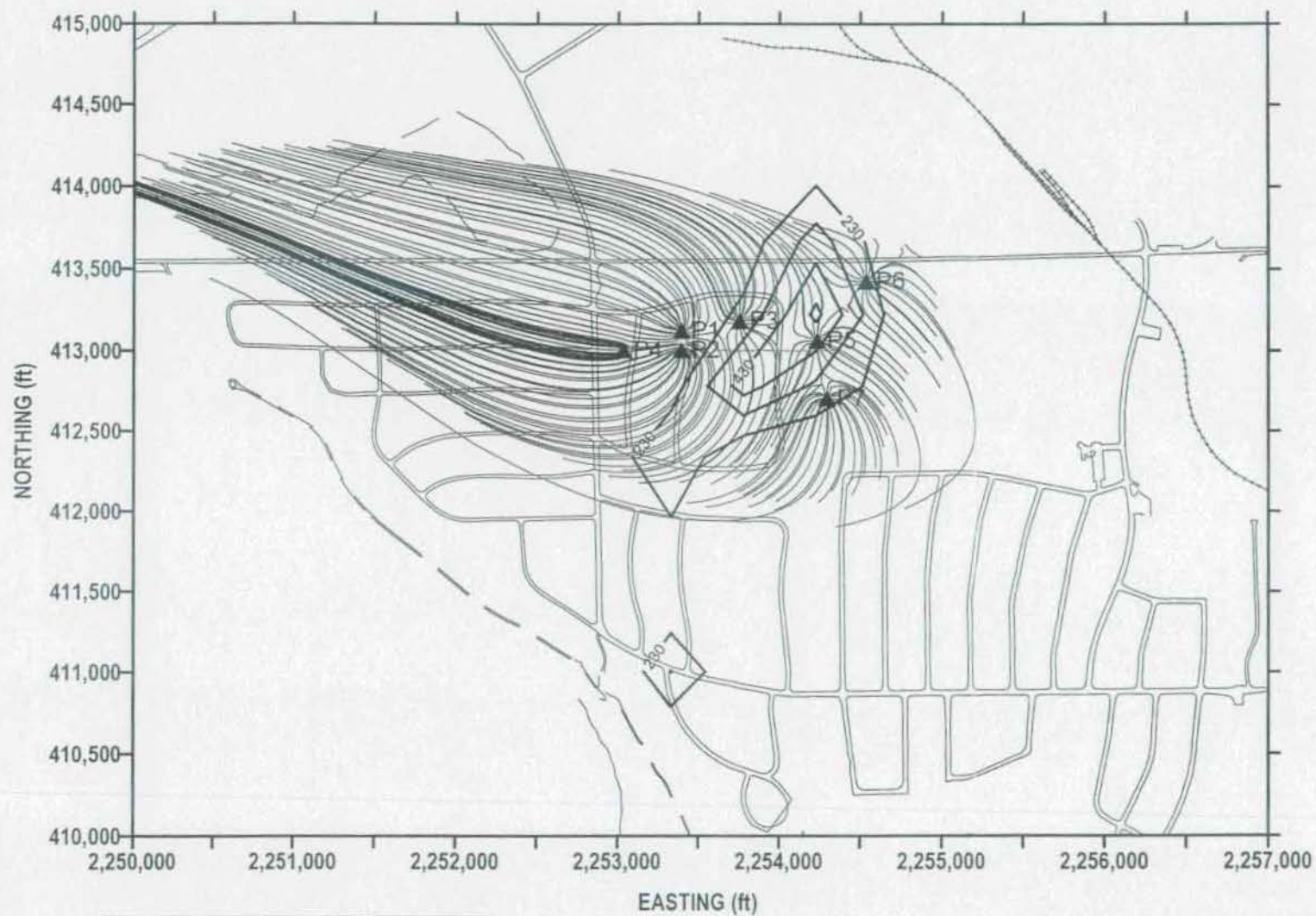
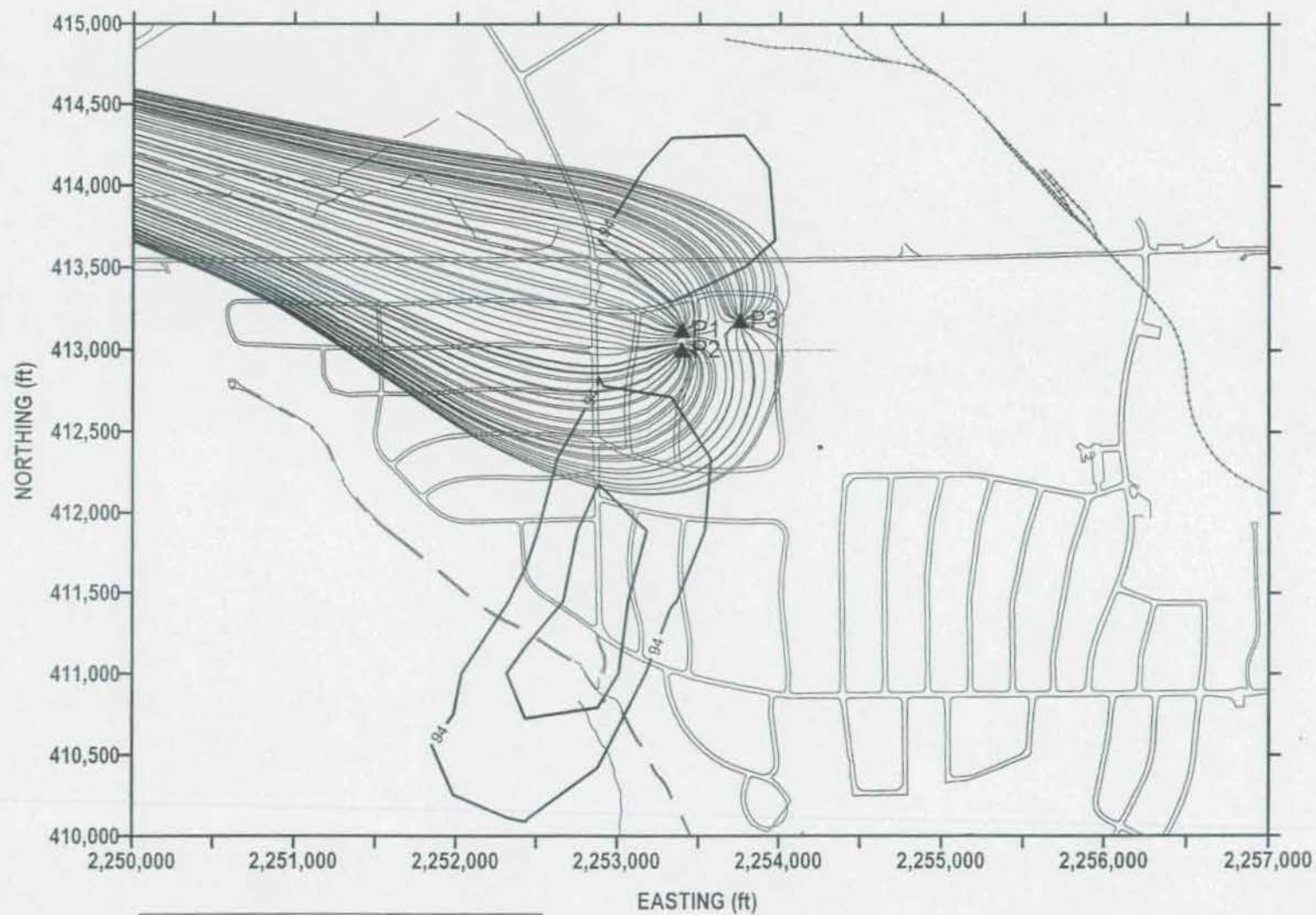
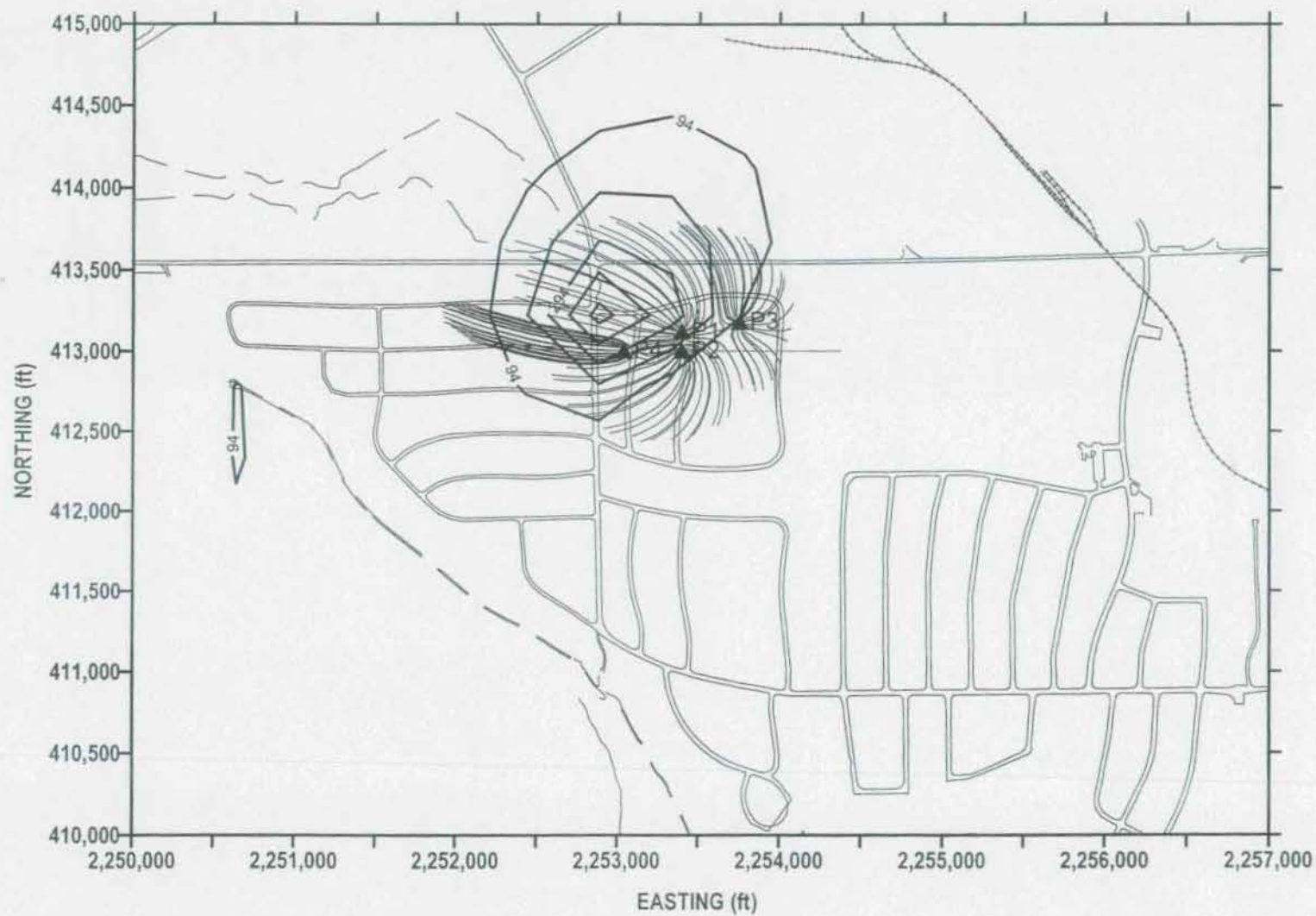


FIGURE 22. Initial DCE concentrations in model layer 2 and pathlines resulting from pumping strategy A, Wurtsmith AFB, Michigan.



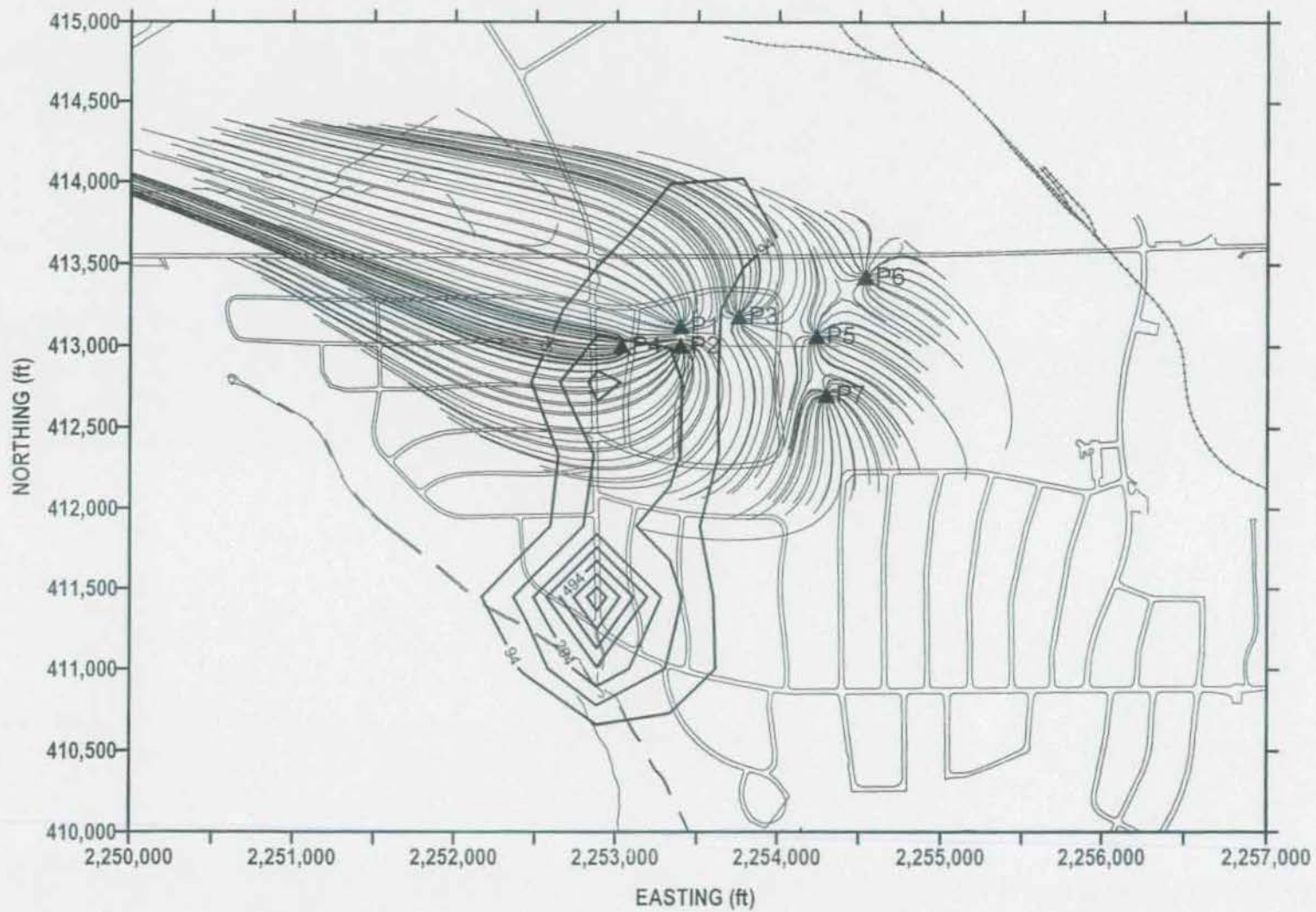
Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 23. Initial TCE concentrations in model layer 3 and pathlines resulting from pumping strategy A, Wurtsmith AFB, Michigan.



Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 24. Initial TCE concentrations in model layer 1 and pathlines resulting from pumping strategy C, Wurtsmith AFB, Michigan.



Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 25. Initial TCE concentrations in model layer 2 and pathlines resulting from pumping strategy C, Wurtsmith AFB, Michigan.

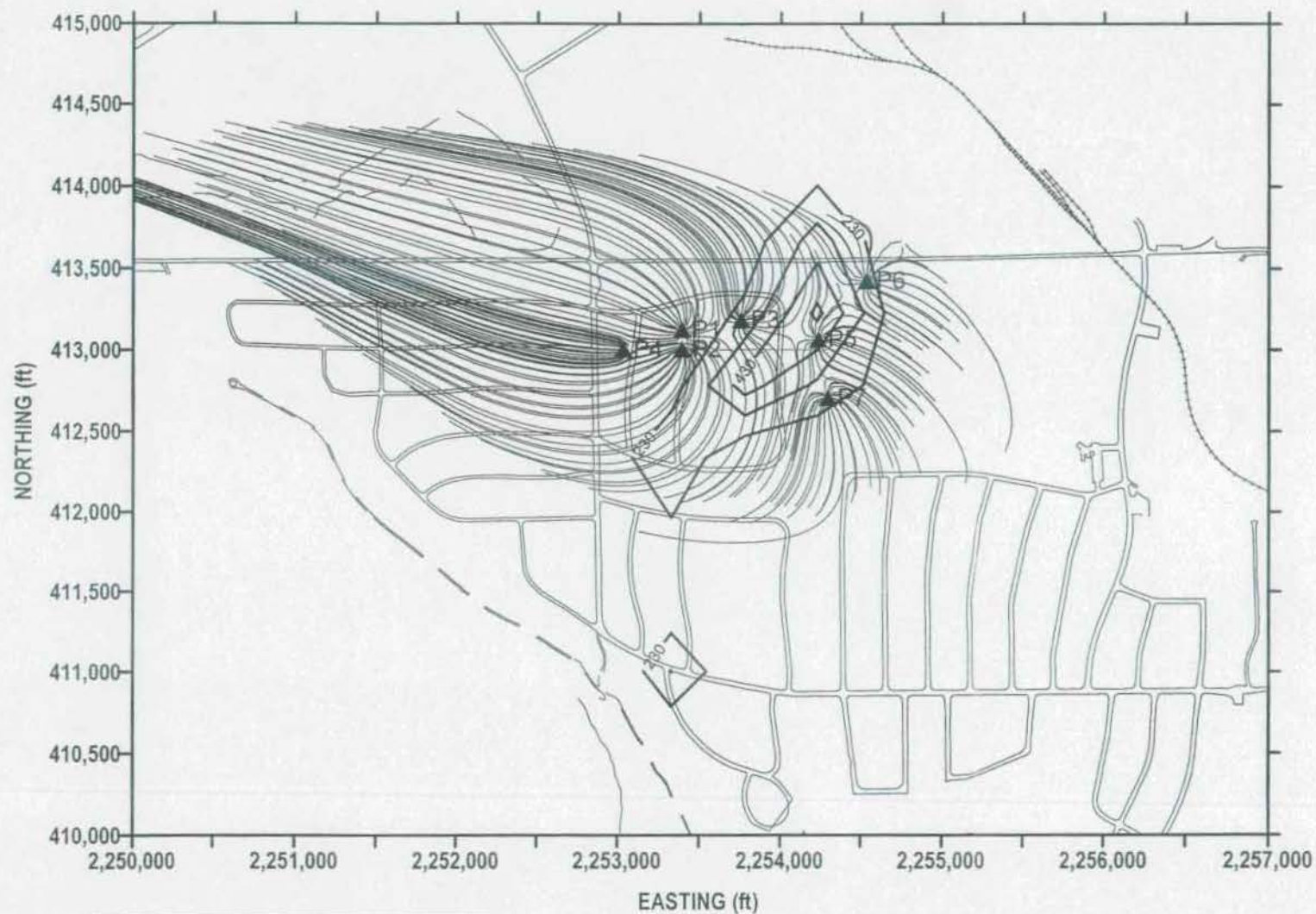
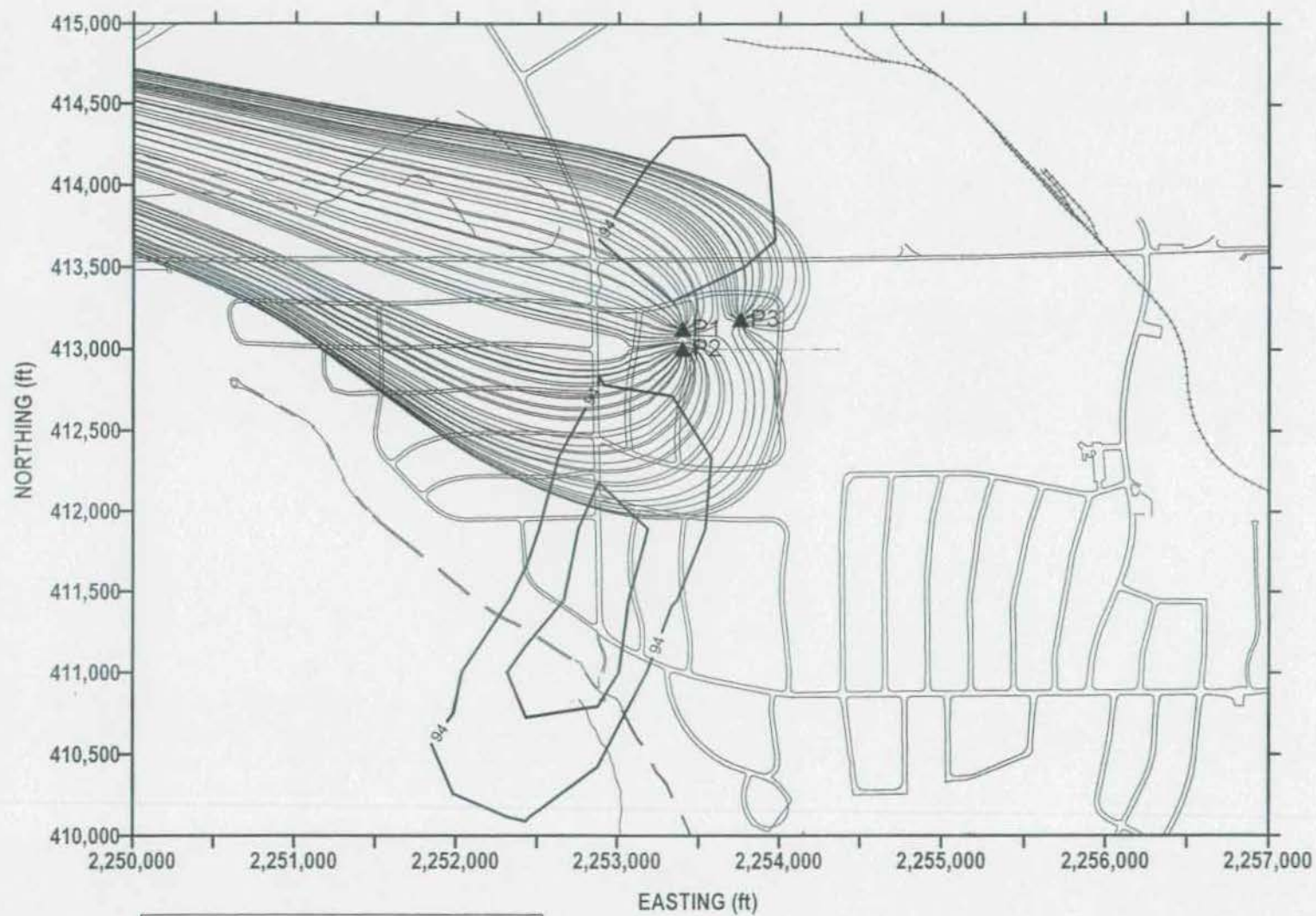
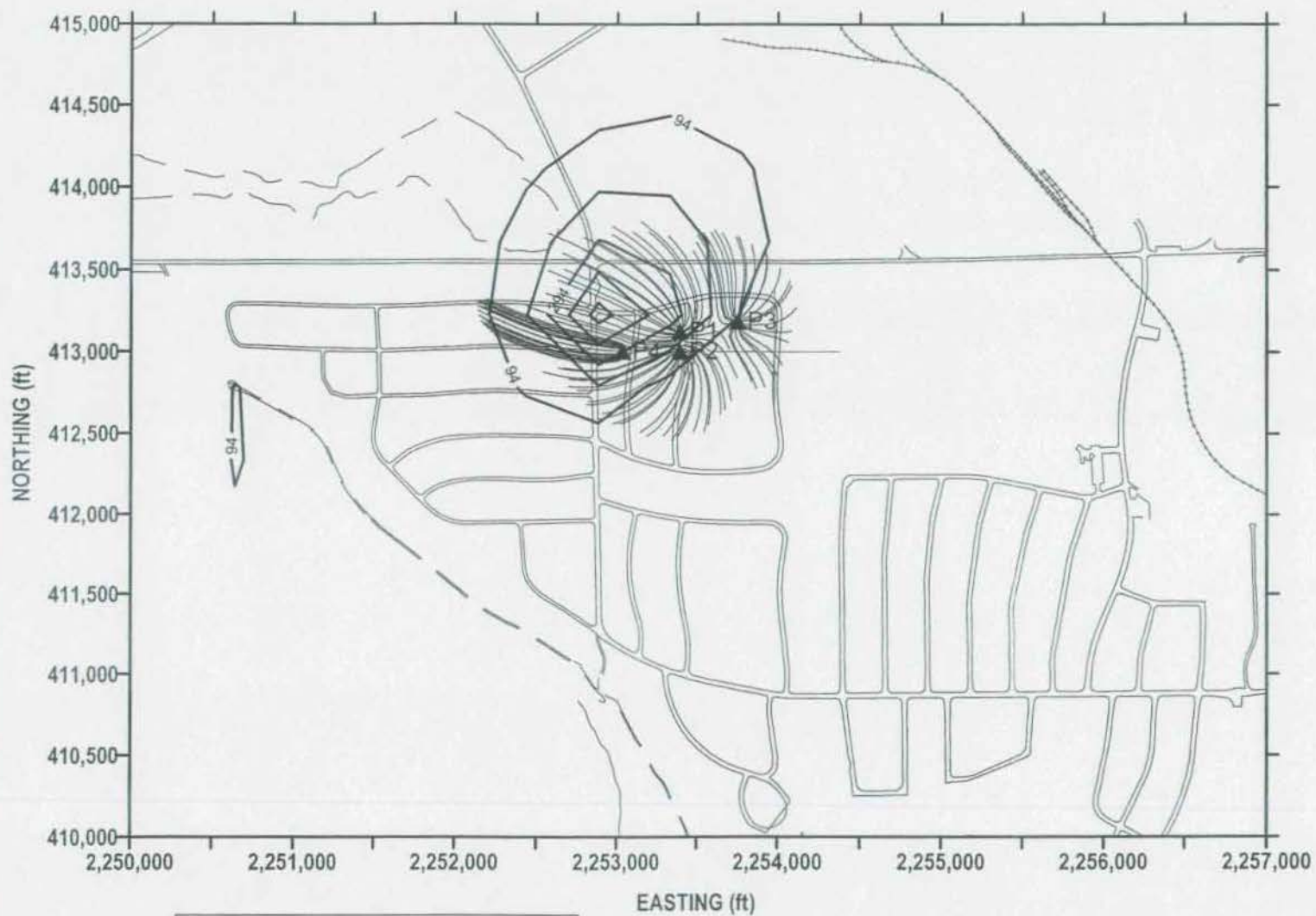


FIGURE 26. Initial DCE concentrations in model layer 2 and pathlines resulting from pumping strategy C, Wurtsmith AFB, Michigan.



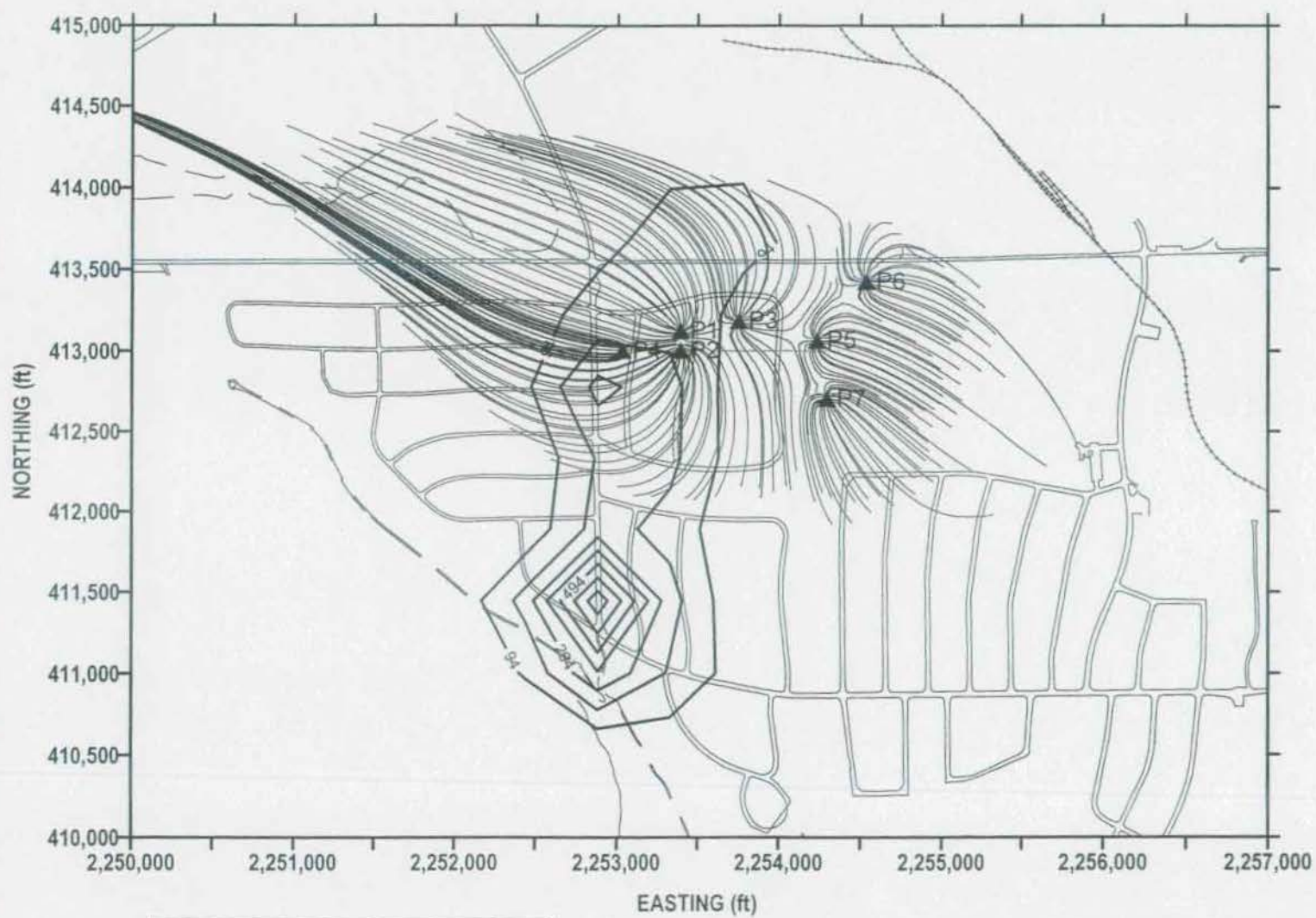
Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 27. Initial TCE concentrations in model layer 3 and pathlines resulting from pumping strategy C, Wurtsmith AFB, Michigan.



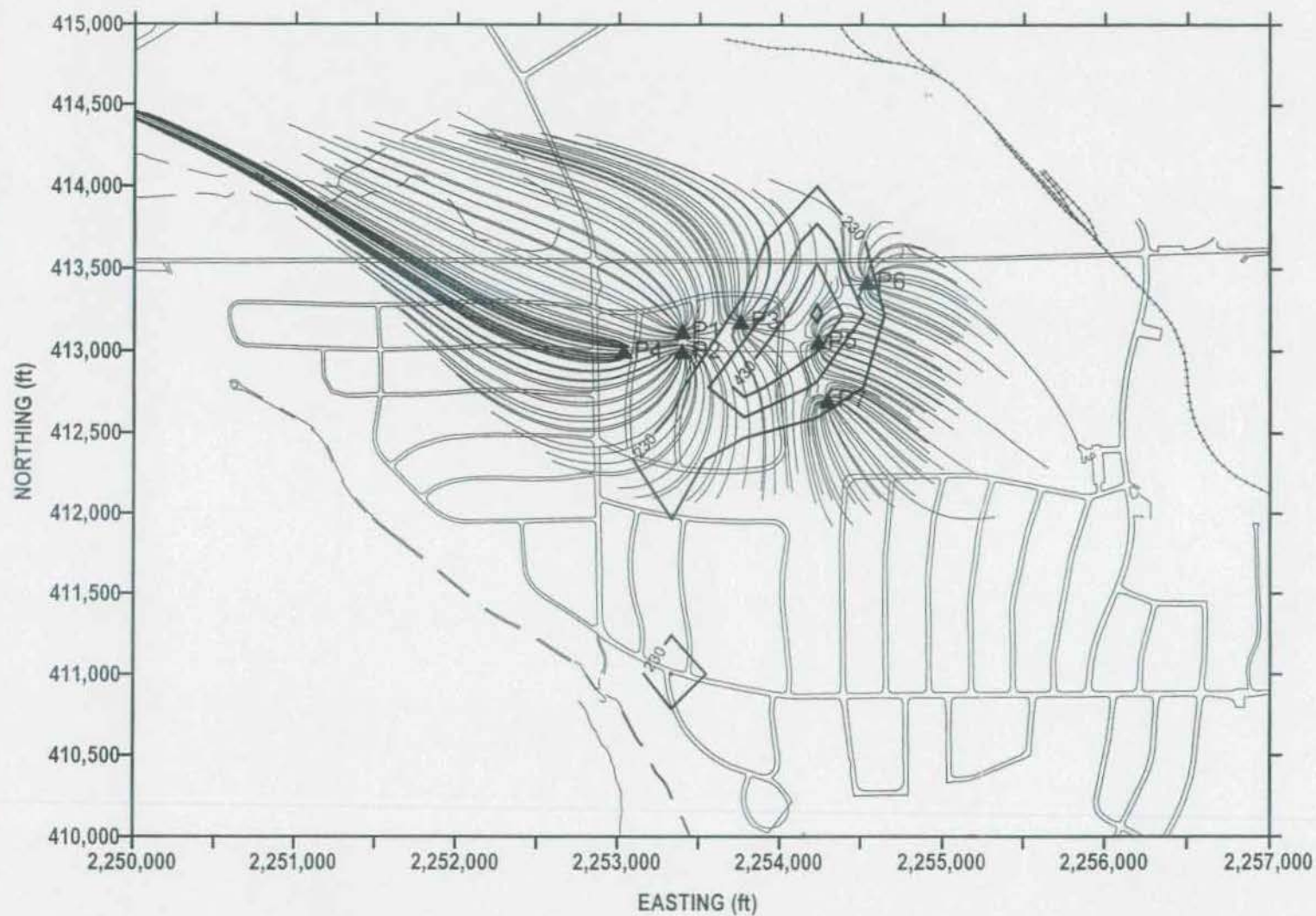
Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 28. Initial TCE concentrations in model layer 1 and pathlines resulting from pumping strategy A when transmissivity is reduced by 50%, Wurtsmith AFB, Michigan.



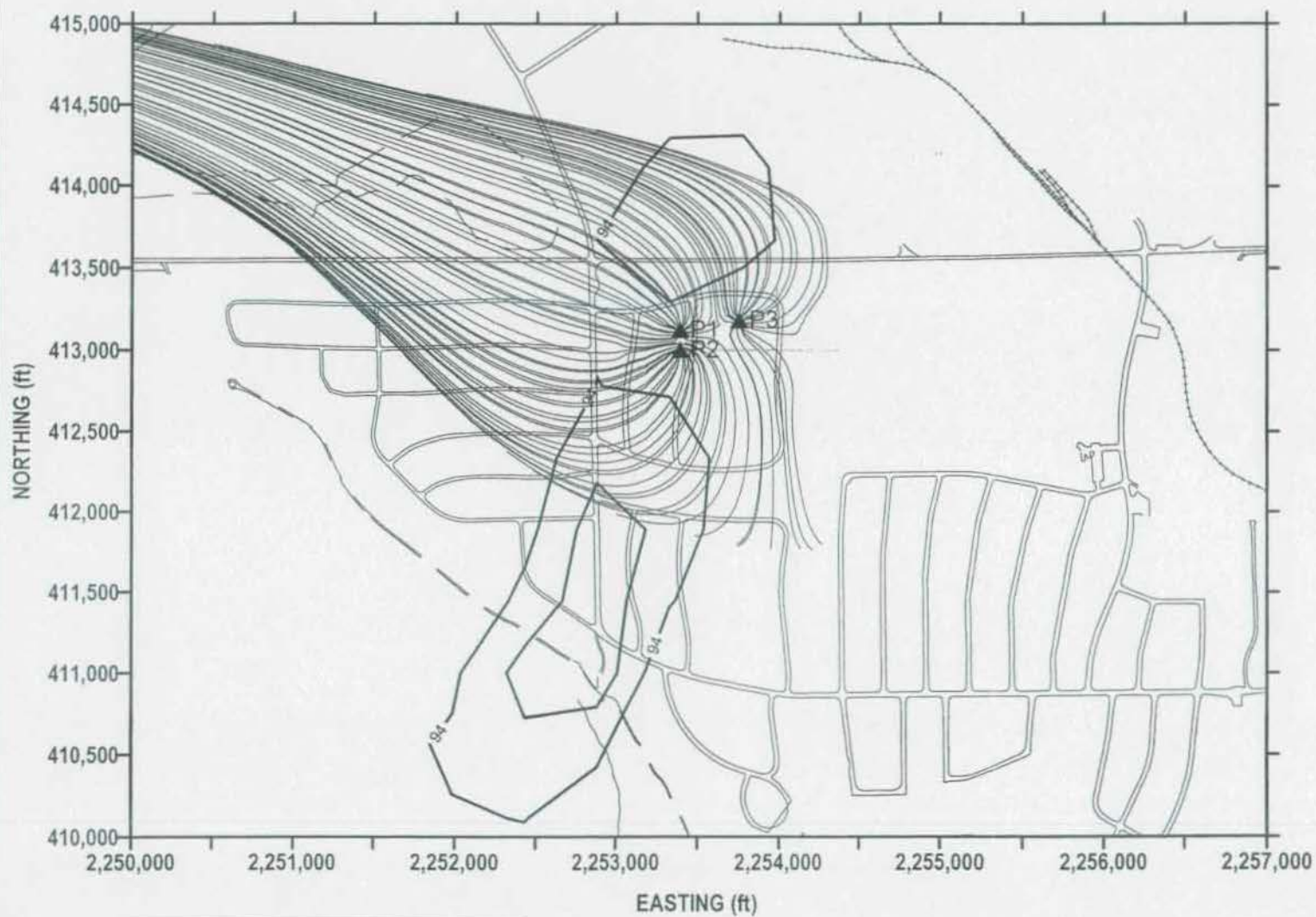
Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 29. Initial TCE concentrations in model layer 2 and pathlines resulting from pumping strategy A when transmissivity is reduced by 50%, Wurtsmith AFB, Michigan.



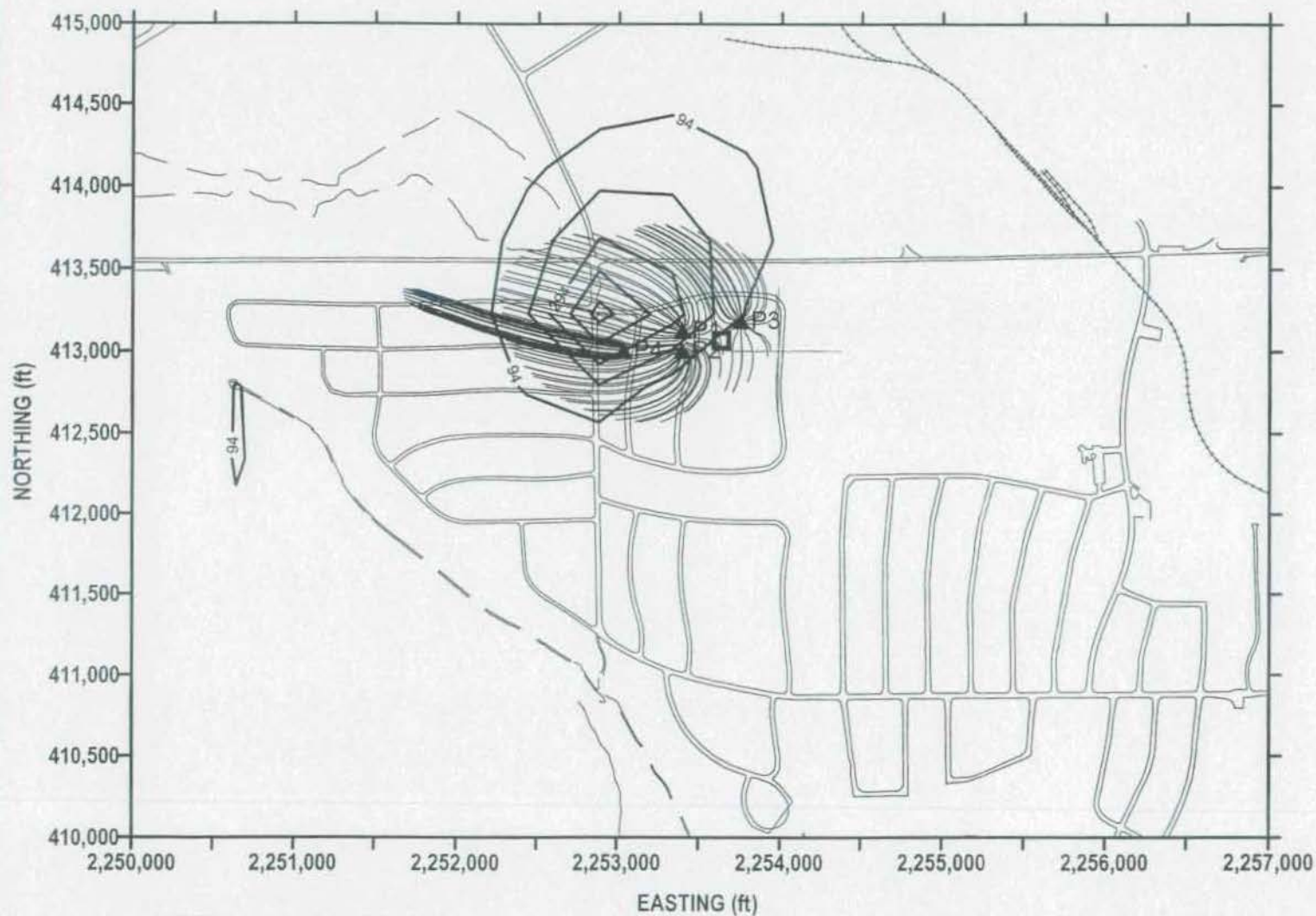
Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 30. Initial DCE concentrations in model layer 2 and pathlines resulting from pumping strategy A when transmissivity is reduced by 50%, Wurtsmith AFB, Michigan.



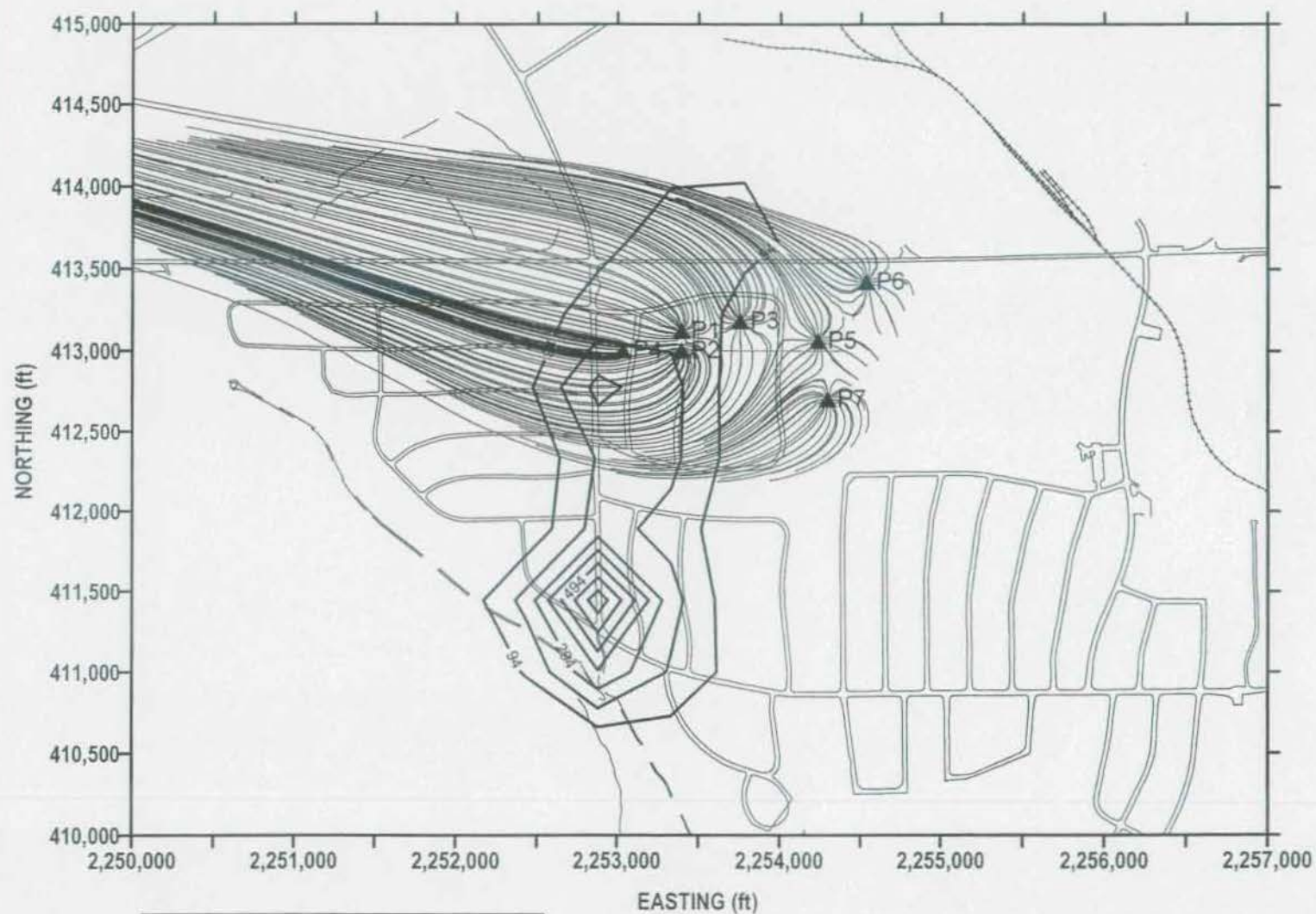
Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 31. Initial TCE concentrations in model layer 3 and pathlines resulting from pumping strategy A when transmissivity is reduced by 50%, Wurtsmith AFB, Michigan.



- Legend
- Contour Interval 100 ppb
- ▲ Extraction Well
- Recommended Monitoring Area

FIGURE 32. Initial TCE concentrations in model layer 1 and pathlines resulting from pumping strategy A when transmissivity is increased by 50%, Wurtsmith AFB, Michigan.



Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 33. Initial TCE concentrations in model layer 2 and pathlines resulting from pumping strategy A when transmissivity is increased by 50%, Wurtsmith AFB, Michigan.

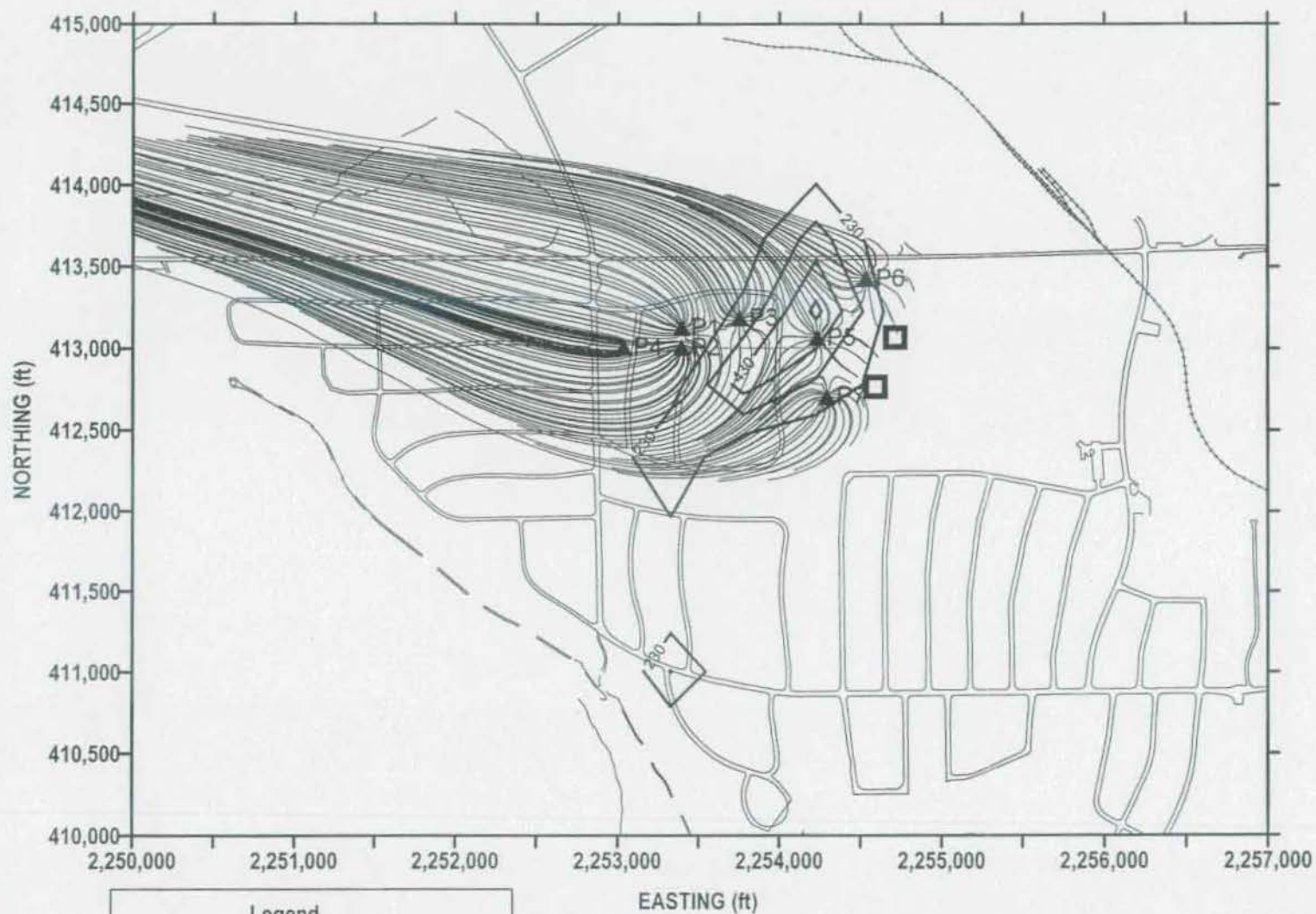
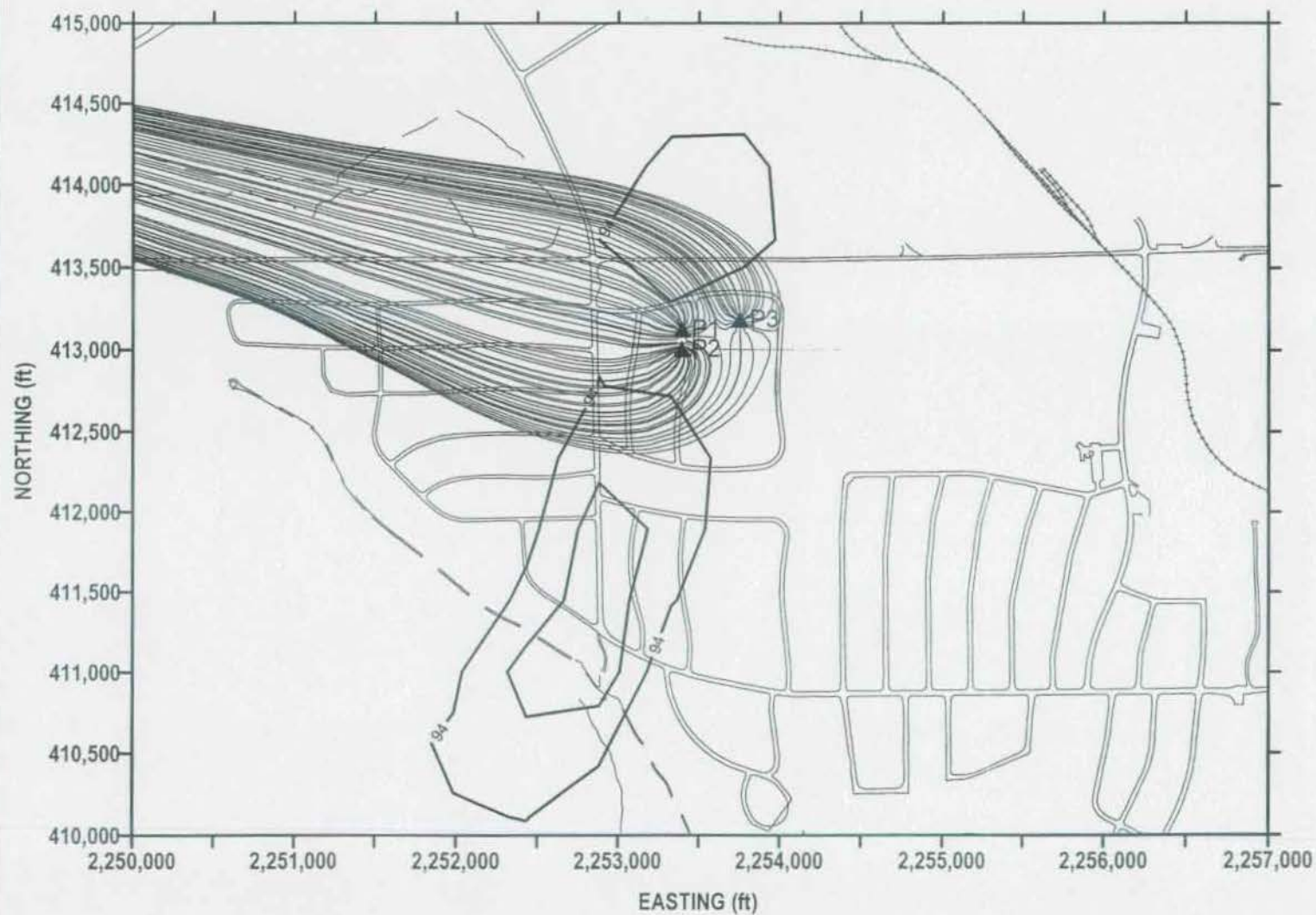


FIGURE 34. Initial DCE concentrations in model layer 2 and pathlines resulting from pumping strategy A when transmissivity is increased by 50%, Wurtsmith AFB, Michigan.



Legend
Contour Interval 100 ppb
▲ Extraction Well

FIGURE 35. Initial TCE concentrations in model layer 3 and pathlines resulting from pumping strategy A when transmissivity is increased by 50%, Wurtsmith AFB, Michigan.